Discussion Paper No. 12-063

Lead Markets for Clean Coal Technologies

A Case Study for China, Germany, Japan and the USA

Jens Horbach, Qian Chen, Klaus Rennings,
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Non-technical summary

Despite the high CO_2 emission intensity of fossil and especially coal fired energy production, these energy carriers will play an important role during the coming decades. In Germany, nuclear energy has to be replaced and in countries such as China or India the high and still growing energy demand requires the use of coal in addition to renewable energy sources. A further argument for coal is the fact that it is in most countries cheaper compared to the use of natural gas.

The paper identifies pulverized coal combustion as the main technological trajectory concerning more efficient coal fuel combustion and explores the potentials for lead markets for the responding technologies in China, Germany, Japan and the USA. We do this by deriving indicators for the lead market success factors as they are described in the literature, taking into account the different regulation schemes in these countries. We concentrate on technologies that have already left the demonstration phase. This is the case for supercritical (SC) and ultra-supercritical (USC) pulverized coal technologies that are already established.

The analysis shows that the typical pattern of a stable lead market only applies to a limited extent. In the 1960s and 1970s, the USA has established a lead market for SC und USC technologies. In the meanwhile, Japan has surpassed the United States, although it started as a typical lag market. Japan has caught up in terms of supply factors, China in terms of price, demand and regulation advantage. China is practicing a leapfrogging strategy, and has already become a leader in the market segment of low and middle quality boilers, whereas Japan and Germany still dominate the world turbine market.

Firm interviews confirmed that Japan and Germany have clear first mover advantages concerning the highly innovative parts of clean coal technologies and in general for 600 °C power plants whereas China has second mover advantages in manufacturing cheap boilers. The crucial question remains if the German firms are able to keep the first mover benefits against the background of the shrinking importance of coal technologies in Germany. Germany and also Japan may lose their first mover advantages because a considerable part of learning from innovation activities occurs when a power plant is constructed in close cooperation with the client. Due to the fact that nearly no new coal-fired power plants are projected in Germany, this country may lose a part of these first mover advantages.

Das Wichtigste in Kürze

Trotz der hohen CO_2-Intensität von fossilen Energieträgern, insbesondere Kohle, werden diese weltweit auch in den kommenden Jahrzehnten eine gewichtige Rolle spielen. In Deutschland ist die Kernenergie zu ersetzen, und in Ländern wie China oder Indien verlangt eine hohe und wachsende Energienachfrage den Gebrauch von Kohle zusätzlich zu erneuerbaren Energien. Ein weiteres Argument für den Einsatz von Kohle ist, dass sie in den meisten Ländern im Vergleich zu Gas günstiger ist.
Die Studie identifiziert die Staubfeuerung als wesentliche technologische Trajektorie im Bereich von Kohlekraftwerken, und bestimmt die Potentiale für einen Lead Market in China, Deutschland, Japan und den Vereinigten Staaten. Dies erfolgt anhand der Ableitung von Indikatoren für die wichtigsten Lead Market Faktoren, die in der Literatur beschrieben werden, wobei auch die unterschiedlichen Regulierungsschemen in den verschiedenen Ländern berücksichtigt werden. Es werden nur solche innovativen Technologien betrachtet, die schon auf dem Markt verbreitet sind. Dies ist der Fall für superkritische (SC) und ultra-superkritische (USC) Kohlekraftwerke, die sich seit Jahrzehnten inkrementell weiterentwickeln.

In der Analyse zeigt sich, dass das Muster eines über Jahrzehnte stabilen Lead Markets für Kohlekraftwerke nur begrenzte Gültigkeit hat. In den 1960er und 1970er Jahren etablierten die USA einen Lead Market für SC und USC Technologien. Inzwischen hat Japan die Vereinigten Staaten überholt, obwohl es als Nachzügler gestartet ist. Japan ist vor allem im Bereich von Angebotsfaktoren wie beispielsweise F+E überlegen, China hat bezüglich Preis-, Nachfrage- und Regulierungsvorteilen aufgeholt. China praktiziert eine sogenannte Leapfrogging-Strategie, d.h. es holt rasch auf, indem es einzelne Stufen überspringt. So wurde China bereits zum Marktführer im Segment von Kesseln niedriger und mittlerer Qualität, während Japan und Germany nach wie vor den Weltmarkt für Turbinen dominieren.

Firmeninterviews bestätigen, dass Japan und Deutschland klare First Mover Vorteile bezüglich der innovativen Kohletechnologie haben, insbesondere für 600 °C Kraftwerke, während China Second Mover Vorteile bei der Herstellung wenig innovativer Kessel besitzt. Die Frage ist, ob Deutschland diese Vorteile angesichts der sinkenden heimischen Bedeutung von Kohle behalten wird. Deutschland und Japan könnten ihren Innovationsvorsprung verlieren, da ein beachtlicher Lernanteil, der bei Innovationsaktivitäten entsteht, durch die Interaktion und Kooperation mit dem Kunden entsteht. Da nahezu keine neuen Kohlekraftwerke in Deutschland geplant werden, können die First Mover Vorteile verloren gehen.

Lead markets for clean coal technologies

A case study for China, Germany, Japan and the USA

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Abstract:
Despite the high CO_2 emission intensity of fossil and especially coal fired energy production, these energy carriers will play an important role during the coming decades. The case study identifies the main technological trajectories concerning more efficient fossil fuel combustion and explores the potentials for lead markets for these technologies in China, Germany, Japan and the USA taking into account the different regulation schemes in these countries. We concentrate on technologies that have already left the demonstration phase. This is the case for supercritical (SC) and ultra-supercritical (USC) pulverized coal technologies that are already established.
The analysis shows that the typical pattern of a stable lead market only applies to a limited extent. In the 1960s and 1970s, the USA has established a lead market for SC und USC technologies. In the meanwhile, Japan has surpassed the United States, although it started as a typical lag market. Japan has caught up in terms of supply factors, China in terms of price, demand and regulation advantage.
This supports the hypothesis that - apart from the demand-oriented lead market model - push factors such as R&D activity play a strong role as well. The advantage of Japan mainly stems from its intensive R&D activities. It can also be observed that some other advantages – such as price and demand advantage – are shifting to China. China is practicing a leapfrogging strategy, and has already become a leader in the market segment of low and middle quality boilers, whereas Japan and Germany still dominate the world turbine market.
The conclusion is that lead markets may switch over time to markets with high growth rates, although first mover advantages exist for some market segments such as turbines. First movers have a strong technological expertise which is important in the catching up process of late followers, and they may even profit from the growth in lag countries by exporting and cooperation activities. Thus international technology cooperation is a beneficial process for all involved parties.

Keywords: Lead Markets, Coal Power plants, Energy Technology, Energy Policy

1 Introduction

Despite the high CO_2 emission intensity of fossil and especially coal fired energy production, these energy carriers will play an important role during the coming decades. In Germany, nuclear energy has to be replaced and in countries such as China or India the high and still growing energy demand requires the use of coal in addition to renewable energy sources. The existing resources of coal are with 14.800 billion tons still sufficient for the next century (Löschel, 2009). 44% of the hard coal resources may be assigned to the USA, 28% to China and 18% to Russia. The resources of lignite (brown coal) are also considerable: 4,200 billion tons (33% USA, 31% Russia, 15% China, 1% Germany). A further argument for coal consists in the fact that it is in most countries cheaper compared to the use of natural gas.

In Germany hard coal (22.8%) and brown coal (25.5%) contributed to nearly half of the whole electricity production in 2007. Following a scenario of IEA (2007), the relevance of the use of coal will not shrink until 2030, for the EU 27 the share of 30% will remain, in China we will still observe a value of around 80% concerning the electricity production. Even if we consider a scenario with a higher use of energy efficiency improvements, China will produce more than 60% of its electricity by the use of coal (see Löschel 2009).

Against this background, cleaner and more efficient coal-fired power plants will have an important role to play for both global energy and climate policy in the future. This study will identify the lead market strategies of four major countries in the global coal power plant market (China, Germany, Japan and the USA) regarding the main innovations of clean coal technology. The lead market approach for environmental innovations as developed by Beise and Rennings (2005) has identified six success factors for lead markets: Comparative price and demand advantages, a high reputation in environmental technology (transfer advantage), similar market conditions (export advantage), a competitive market structure and ambitious environmental regulation. We will also take further supply side aspects and the very different regulation schemes in those countries into account (see also Rennings and Cleff 2011, and Tiwari and Herstatt 2011). Our ex-post analysis tries to identify the existence of lead markets for the most important efficient, “clean coal” technologies compared to the scenario that a “second follower strategy” fits better for these technologies.

The most important technological trajectory of fossil fuel power plants is the pulverized combustion with a share of 90% of coal-fired capacity worldwide (WCI 2005, see also Rennings and Smidt 2010), so that this technology will be in the focus of our case study. Another reason is that we want to concentrate on technologies that have already left the demonstration phase. This is the case for subcritical, super- and ultra-supercritical pulverized coal technologies that are already established whereas for technologies such as Carbon Capture Storage (CCS) no diffusion curves can be derived yet due to their early phase of innovation.

The paper is structured as follows: Section 2 describes the relevant clean coal technologies. In Section 3, we derive their diffusion curves for Germany, China, Japan and the USA. Section 4 applies the lead market approach to the case of efficient coal technologies. Section 5 takes additionally supply side factors into account. In Section 6, we report on strategies for German firms based on expert interviews. Section 7 summarizes the results and concludes.

2 Coal Power Plant Technology Description

In general terms, a clean coal technology may be defined as a “technology that when implemented improves the environmental performance and efficiency as compared to the current state-of-the art in coal fired power plants” (Buchan and Cao 2004). Coal-fired power stations with pulverized bed combustion are differentiated and called by the steam conditions when entering the turbine, although it is not the only property which characterizes a coal-fired power station. Other important characteristics are the condenser pressure or the efficiency of the turbine (RWE Power AG 2011, IEA 2010a).

The steam conditions are divided in subcritical-, supercritical- and ultra-supercritical-conditions. Steam is called supercritical, when the steam parameters exceed the critical point[1]. The higher the temperature and pressure of the steam is, the higher the efficiency of the power plant.[2] A subcritical power plant works with a steam temperature about 540 °C or less and a pressure about 160 bar, which lies under the critical point. This technology is obsolete and

[1] Critical point describes the temperature and pressure above which the working fluid – in this case water – no longer turns into steam but instead decreases in density when it is heated above 'boiling point'. By eliminating the transition into steam (phase change) the efficiency of the process can be improved. For water the actual conditions are temperatures and pressures of over 374°C and 221.2 bar respectively.

[2] The rule of thumb in power plant construction is that each additional bar causes a 0.005% increase in degree of efficiency and each additional degree Celsius causes a 0.011% increase.

was removed by the supercritical power plants. Here, the steam temperature lies between 540 °C and 600 °C and the pressure between 230 bar and 270 bar. Temperatures of 600 °C with a pressure of 270 bar are state of the art and are called ultra-supercritical. Applying this technology, an efficiency of 40% - 43% can be achieved. Technologies characterized by temperatures of 700°C and pressures of 375 bar will be called advanced ultra-supercritical.[3] The so-defined advanced ultra-supercritical power plants are currently applied in some projects only, because of the high costs of materials which can resist this temperature and the pressure (IEA, 2010). Therefore nickel alloys will be developed. An efficiency of 50% can be reached with this technology (Energy 2.0, 2008).

The main improvements in power plant technology focus on efficiency and on the decrease of emissions. To achieve these targets, knowledge of many disciplines is required, because improvements are often based on incremental changes in different technologies. The diffusion of new technologies in coal-fired power plants is slow due to a long average life time of 35-40 years, and the risk of the high investments which leads to risk-averse investment decisions (Rennings et al., 2010).

Our case study will analyze the diffusion of supercritical and ultra-supercritical power plants as innovative solutions compared to the older subcritical plants.

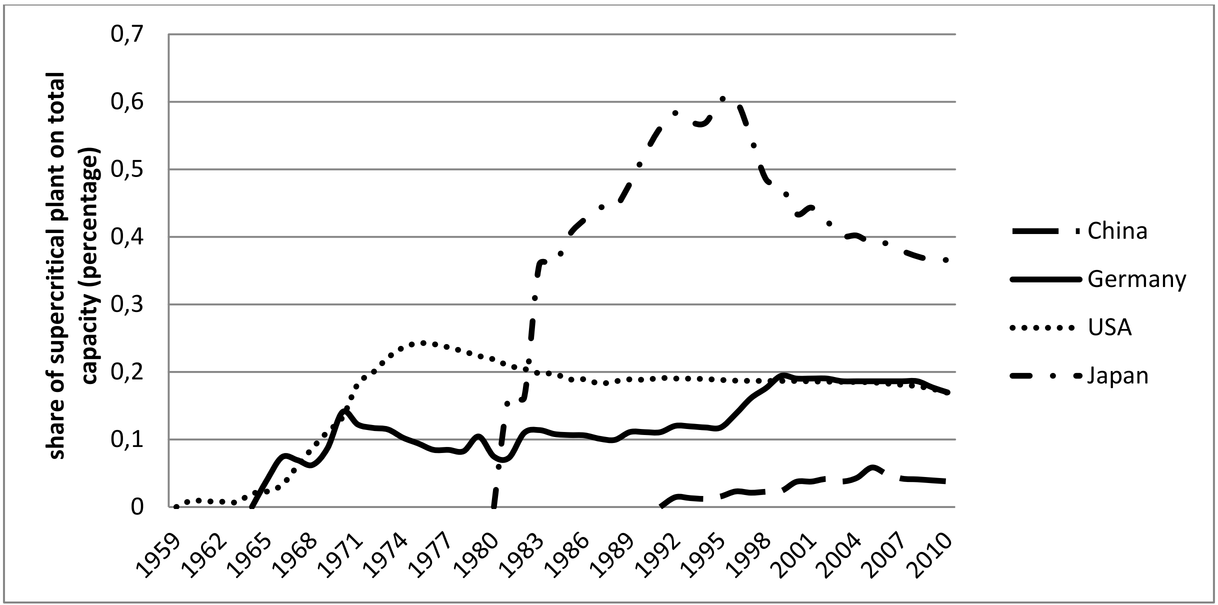
3 Diffusion Curves

Diffusion curve of supercritical pulverized coal technology

Supercritical pulverized coal technology is one of the most common technologies among coal-fired electricity generation. This technology has been used for several decades (since 1959) and realises its diffusion in the United States, Germany, Japan and China. Figure 1 shows the diffusion curve over time as the share of supercritical power plants on the entire installed capacity of coal-fired power plants in a country, which means the accumulative installed capacity of supercritical power plants/ total installed capacity per year.

[3] The IEA coal database already defines technologies as ultra-supercritical that are characterized by a steam pressure of more than 250 bar combined with a steam temperature of at least 550 °C. The diffusion curves in Section 3 are calculated following this definition.

Figure 1: Diffusion curve of Supercritical pulverized coal technology in selected countries



Source: IEA (2011a), own calculations.

USA

The United States was the leader in designing and manufacturing supercritical pulverized coal technology in the late 1950s. In 1959, the first coal-fired supercritical power unit Avon Lake 8 was commissioned in the USA and in 1960 four more supercritical power units followed. Then this technology developed well especially after the material problems were overcome in the second half of 1960's (Rennings and Smidt, 2010). The share of supercritical power plants rose constantly and reached its peak (24.1%) in 1976 and then it came to a stop in the late 1970's and remains by 20% up to now.

Germany

Germany quickly followed the USA in adopting supercritical power plants since 1965. Just like in the United States, the diffusion of supercritical plants seemed promising in the beginning. However, just after reaching a market share of 14.1% in 1970, the diffusion of supercritical power plants stopped and declined again to about 7.3% in 1981. After the reunification of Germany in 1990 the ratio of supercritical to subcritical power units rose again. The government's commitment to advance the state-of-the-art pulverized coal technology was the most important driver to the development of supercritical technology. The peak of the diffusion rate of supercritical power units reached 19.4% in 1999 and it declined to 17% in 2010. Beginning from 1999, Germany concentrated on the construction of ultra-supercritical plants characterized by steam temperatures of 550 °C and more (following the definition of The IEA coal database, see also Figure 2).

Japan

Japan started constructing supercritical plants in the 1970s, and caught up in the next decades. Influenced by the oil price crisis, the share of Japanese supercritical power plants quickly rose from zero in 1980 to 60.2% in 1996, at an annual growth rate of 27.3%. The total installed capacity in 1996 was 11900 MW in Japan. After then it started to decline to 36.6% in 2010.

China

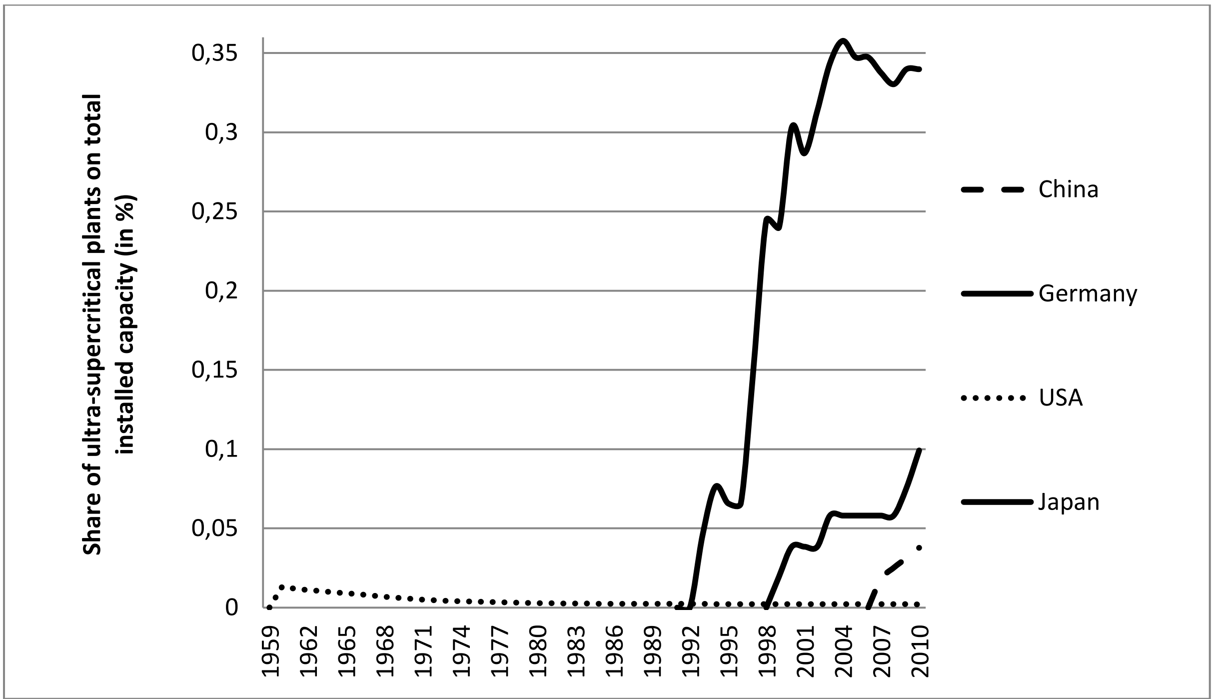
China is the last country regarding the development of supercritical pulverized coal technology of the four countries. China started using supercritical technology in the 1990s with the procurement of ten units from Russia. Since then, many more supercritical units were built and approximately 27 were in operation at the end of 2010. Sixty percent of the new plants that started construction after 2005 and represent a total of 37.8 GW (600 MW each) are supercritical. From 2010 to 2020, new power plants with unit capacities of 600 MW and more will all be required to be supercritical and about half of the newly built power generating units will be ultra-supercritical. Consequently, supercritical units will account over 30% by 2020 (Huang, 2008).

It seems that the USA first takes over the role of a lead market in the 1960's and during the following 20 years. Other countries followed the American innovation design, such as Germany in the 1960's and Japan in the 1970's. So far, the lead markets model argues that lead markets do not switch to other countries but are "stable". This has been supported by several empirical analyses such as the diffusion of cellular phones, facsimile machine; diesel motors with direct injection, etc. (see Beise 2001, Beise and Rennings 2005). However in this case, the diffusion curves overlap by Japan in the early 1980's since America stopped to build new supercritical power plants (Rennings and Smidt, 2010).

Diffusion curve of ultra-supercritical pulverized coal technology

The diffusion of ultra-supercritical pulverized coal technology (USC) paints a similar picture to what was already indicated in the analysis of supercritical pulverized coal technology. The first USC plant in the world was Ohio Power's (now American Electric Power) Philo unit 6 in the USA in 1960. Not as expected, America decided to abandon this technology on the domestic market since 1960, only one year after the first ultra-supercritical pulverized power plant was built. Since then it lost its lead market role although it was the first who designed and manufactured ultra-supercritical power plants. Ultra-supercritical power plants first appeared in the USA, but other countries joined in applying the technology. For example, instead of Germany, Japan picked up ultra-supercritical pulverized coal technology in 1993. As a second mover, Japan was the major driver for USC technologies during the 1990s and became the technology leader before 2005. Germany started with the diffusion of this technology in 1999. Although China is still the last country that introduced this technology in 2007, commercial adoption of ultra-supercritical technology is expanding rapidly. Supercritical and USC used to represent a small percentage of the newly ordered power plants (10%-30%) before 2002, but in recent years they represent more than 60 percent of all coal power plants in China. And there are 23 USC power plants with 33 GW-level USC units operating in China at the end of 2010, while 11 more were under construction (CEC, 2011).

Figure 2: Diffusion curve of Ultra-supercritical coal-fired power plants



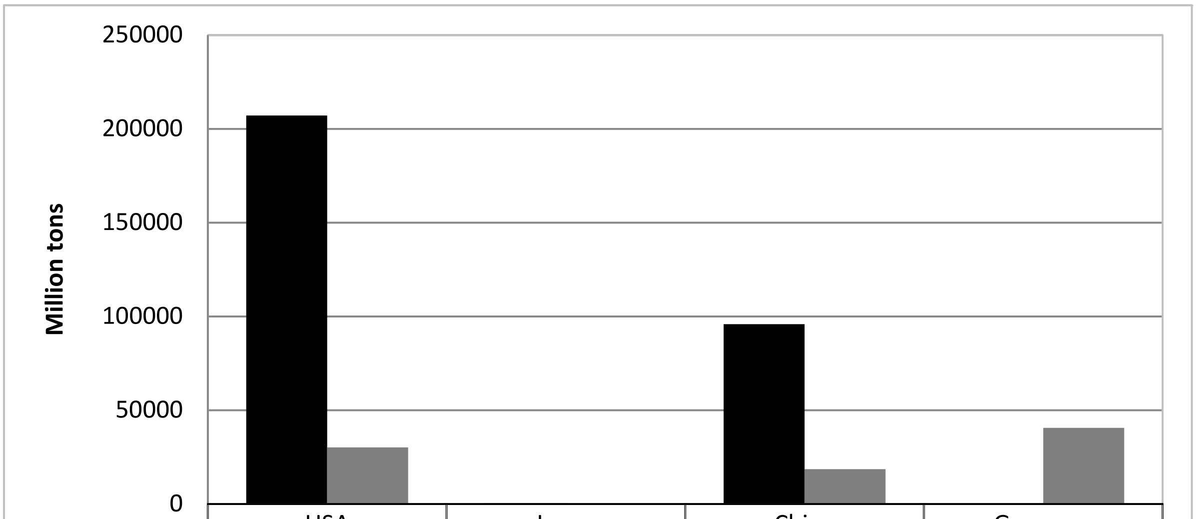
Source: IEA (2011a), own calculations.

4 Lead Market Factors

4.1 Price advantage

The price advantages can be measured by using different indicators: proved reserves, fuel costs, absolute and comparative cost advantage. First, proved reserves are defined by the IEA (2007, p. I. 9) as all resources "…that are not only confidently considered to be recoverable but also can be recovered economically, under current market conditions." This means that using proved reserve data makes it unnecessary to take national differences in accessibility and extracting costs into account. It is an indicator of the supply side for relative cost advantages regarding resources. Figure 3 shows the proved recoverable coal reserves [in million short tons] in the different countries.

Figure 3: Proved hard and brown coal reserves in 2008 of selected countries



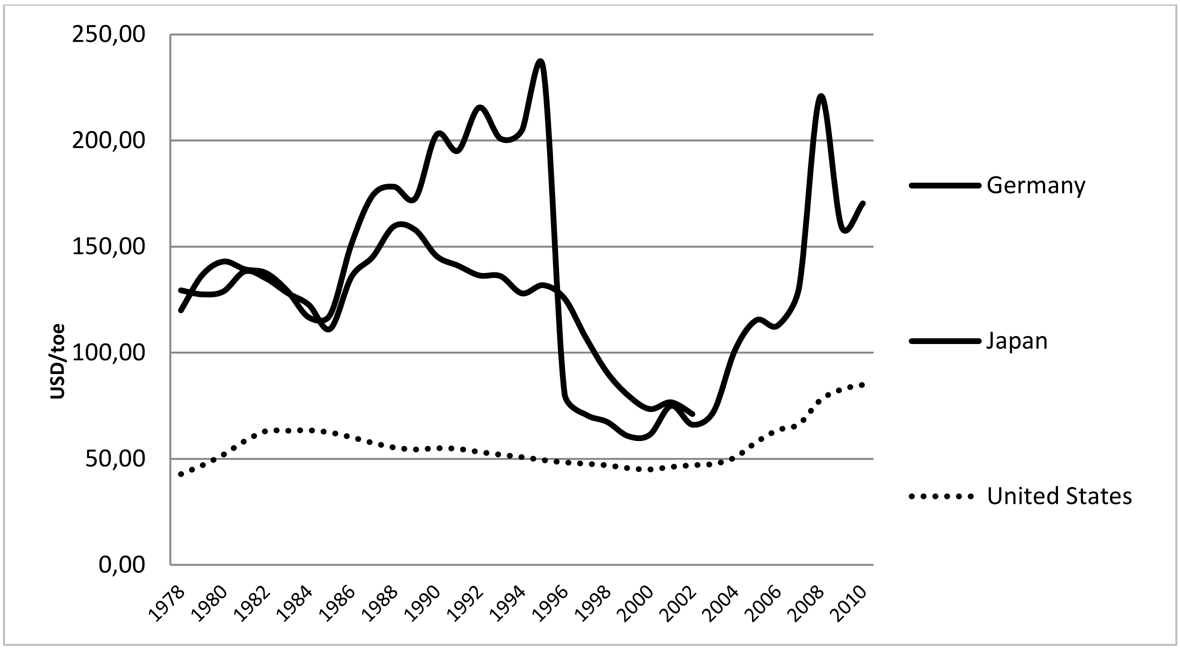
	USA	Japan	China	Germany
Hard coal	207119	340	95900	99
Brown coal	30176	10	18600	40600

Source: IEA (2011b).

There is a great inequality concerning the spread of reserves across the globe. If it is assumed that importing fuels is more expensive than extracting own reserves, then the endowment of a country regarding coal reserves decides whether it has a price advantage or not. The usefulness of proved resources as an indicator for price advantages is however limited. It is possible

that a country is not able to make use of its reserves, because it is not permitted by the national energy policy. Then, of course, the rich reserve with coal is no advantage for a country.
Reliable data concerning proved reserves are only accessible for very few points in time. No time series are available and the publicly availably publications only cover the time from the late 1990s onwards. The data used for the analysis are from IEA statistics on “Coal information 2011”.
As Figure 3 shows, the United States own the far largest coal reserves in the world (IEA, 2011). The structure of coal reserves in both USA and China is similar. 87.3% of total reserved coal is hard coal in USA and 83.8% in China. Germany has only abundant reserves concerning brown coal and Japan’s total proved coal reserves are negligible. Following Beise’s argumentation (Beise 2001), USA has a price advantage caused by its abundant coal reserves compared to the other countries.
Fuel prices also give information about the price advantage of a country. Figure 4 shows the steam coal price paid by utilities in each country (except China) for electricity generation (US$/toe). Data is often not reported for countries that rely to a large extent on domestic coal production and for those countries whose mining sector is state owned. This applies for China, where data about coal prices is not available. Furthermore, tax reductions and other privileges may distort the picture painted by the analysis of fuel costs. It may occur that a country has to pay high import prices and has no reserves that it can rely on, but domestic regulation compensates for the high fuel prices.

Figure 4: Steam coal price paid by utilities for electricity generation

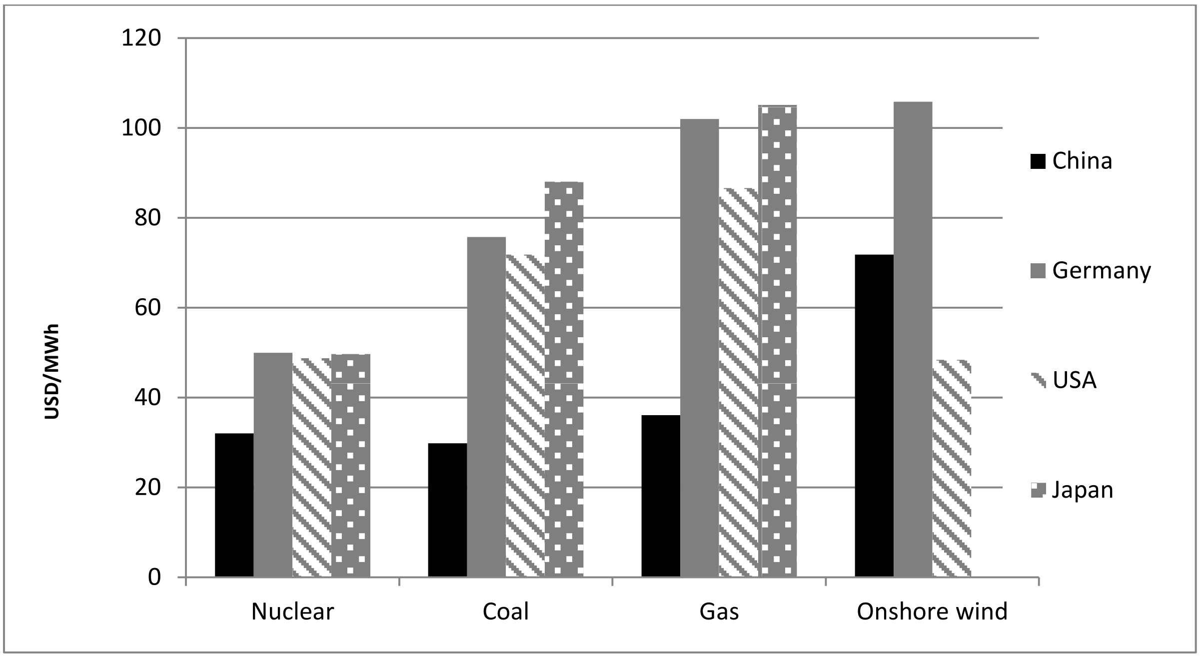


Source: IEA (2011c).

The analysis of the fuel price data shows that the USA has a definite price advantage compared to Japan and Germany. Not only did American utilities sometimes pay less than a third of what Japanese and German utilities had to pay, the price for steam coal in the US also remained relatively stable. Germany is a perfect example of how state regulation can influence the costs of utilities. Until 1994, German utilities were forced to buy steam coal out of domestic production, which operated – due to unfavorable geological conditions – on an uneconomical level. This led to steam coal prices exceeding those in Japan by far. Prices dropped immediately after the act was abolished in 1994. The USA maintains its price advantage throughout the entire time.

A third indicator for the price advantage of a country is the absolute cost advantage in terms of electricity generating costs for the main energy sources (see Figure 5).

Figure 5: Leveled cost of electricity from four energy sources in selected countries[4]



Source: IEA (2011d).

The analysis of the electricity costs for the main energy sources shows that China has a definite cost advantage compared to the other three countries whereas Japan is characterized by the highest electricity costs reflecting the low endowment with energy resources.

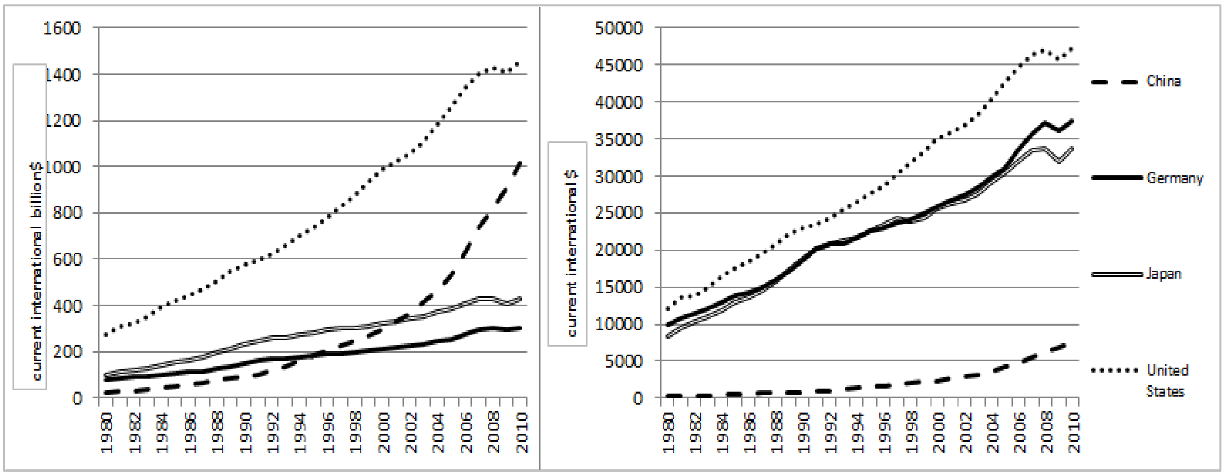
[4] USA, Germany and Japan: Black coal pulverized coal combustion technologies; China: Black coal supercritical coal combustion technologies.

4.2 Demand advantage

Per capita income can be used as an indicator for demand advantages. The wealth of a nation plays a positive role on the rate and time of adoption of innovations (Dekimpe et al. (1998) and Vernon (1979)). From a supply perspective, it may increase the motivation to invest in new technologies and from a consumer perspective it reflects a greater willingness to pay for new products. However, the correlation between income and the rate a nd time of adoption of innovations has been mostly proven for consumer goods (Beise 2001, p. 91) whereas the innovative behavior of firms strongly depends on further factors such as the existence of innovative capacities or a highly qualified staff. Figure 6 shows the total GDP and GDP per capita (current international $, in Purchase Power Parities (PPP)) in the selected countries.

Figure 6: Total GDP and GDP per capita (current international $, in PPP) of selected countries

Total GDP GDP per capita



Source: Word data bank (2011a).

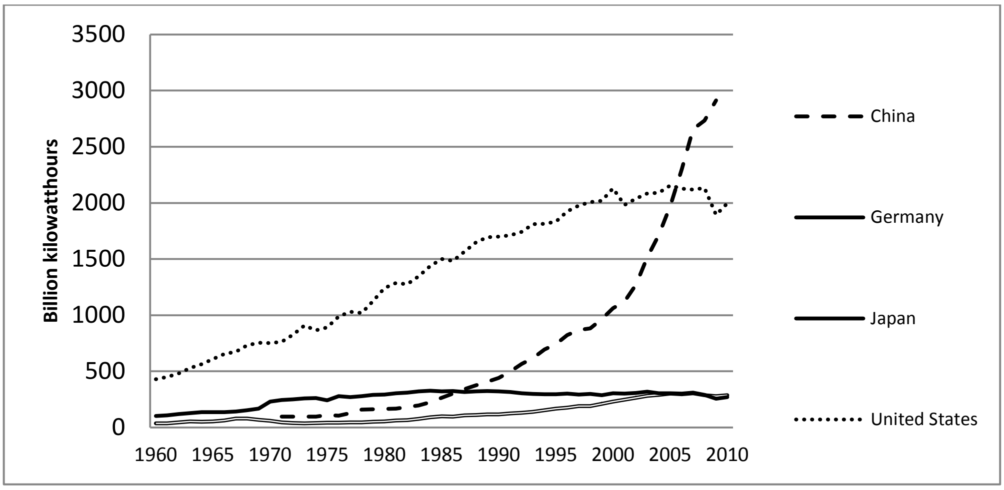
Among the four countries examined in this study, the USA shows the highest total GDP. China´s total GDP grew rapidly during the last two decades and passed Germany in 2007 and Japan in 2009, becoming the second largest economy in the world.

The GDP per capita shows another picture: The USA is characterized by the highest income per capita, Germany and Japan follow closely. China's income-per-capita in 2010 was only 4354 $. Summarized, the USA seems to have a demand advantage over the other three countries, followed by Japan, then Germany and China. Given the high growth rate of GDP during the last decades, China can however be expected to take over the lead regarding demand advantages in future.

Electricity intensity can be interpreted as a second indicator for demand advantages. It can be assumed that those countries with a high coal-based electricity production will also show high demand for new and efficient coal-fired technologies. The figures 7-9 show the electricity production from coal sources, the total thermal electricity intensity of GDP and the share of coal on total electricity output in the selected countries.

Since 2010, China is the second largest electricity consumer with 4190000 Gigawatt hour (GWh), very close to USA with 4361401 GWh in 2010. However, after nearly 10% annual economic growth in the past decades and tripling its coal electricity production since 1970, China has already surpassed the USA regarding coal electricity production since 2006. In contrast to the stable trend in the three other countries, there was a rapid increase in the coal electricity production since 2006.

Figure 7: Electricity production from coal sources in selected countries between 1960 and 2010 [GWh]

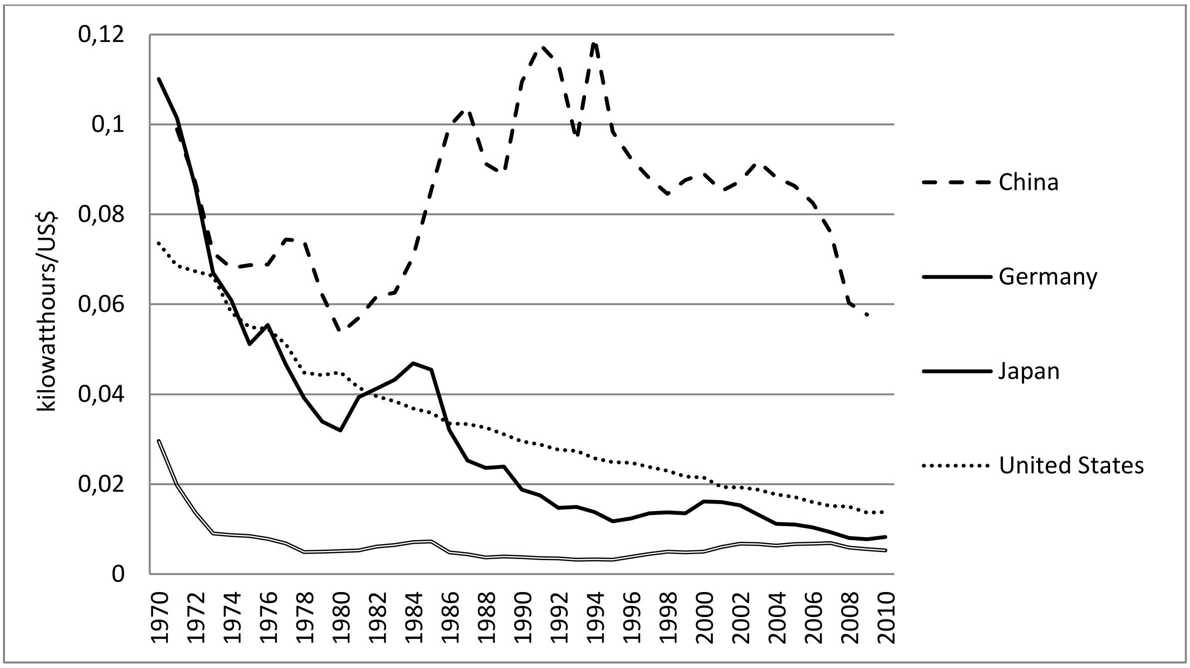


Source: World bank database (2011b).

Figure 8 shows the amount of production of electricity generated from coal per $ GDP, i.e. the electricity intensity of each country. In 2010 China produces 0.07 kWh per $ GDP and thus has a demand advantage, while the USA (0.014 kWh/$) cannot keep their “leading” position. Germany (0.008 kWh/$) and Japan (0.005 kWh/$) are less electricity intensive.

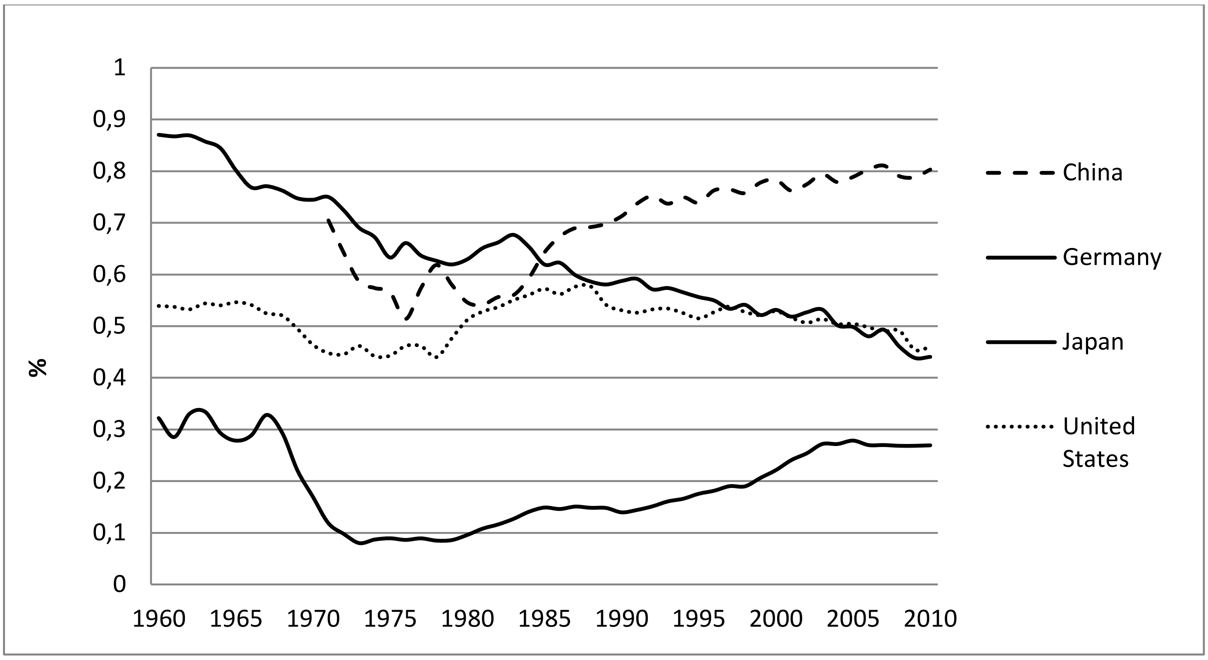
As technical equipment gets more efficient in general and electricity prices keep rising, all countries have experienced a decrease in electricity intensity over the last decade. Especially in China, the electricity intensity declined by 41.7% during 1971-2009.

Figure 8: Total thermal electricity intensity of GDP of selected countries between 1970-2010



Source: World bank database (2011b).

Figure 9: Share of coal on total electricity output of selected countries

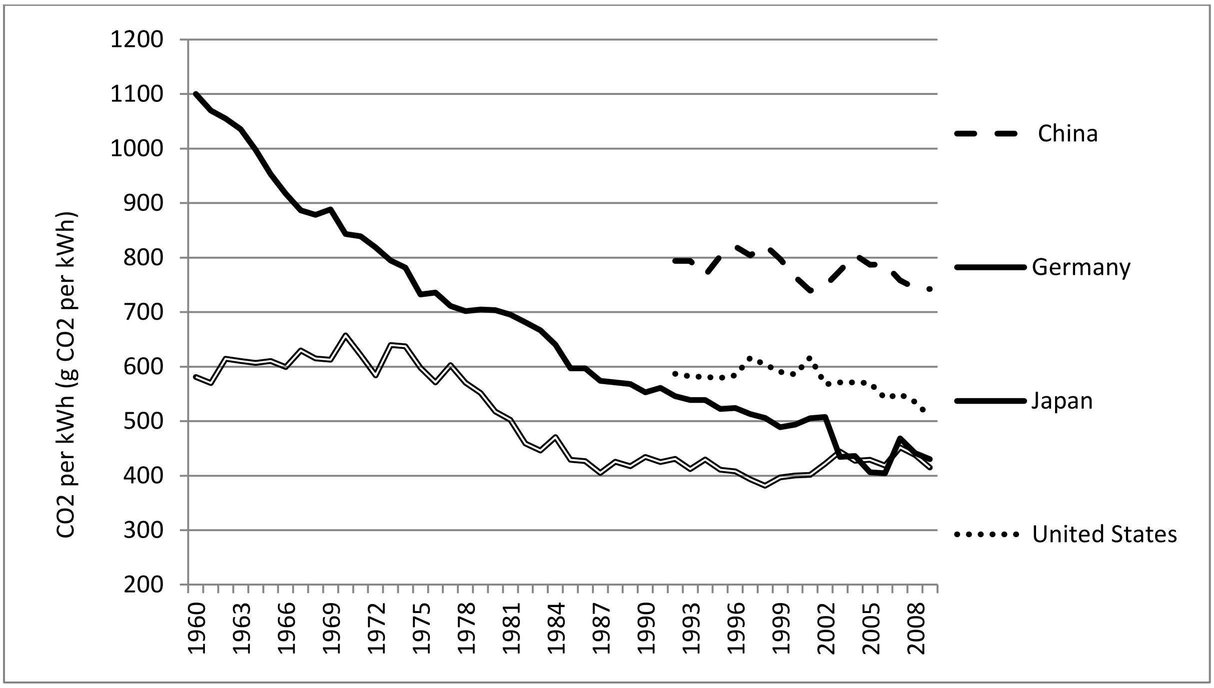


Source: World bank database (2011b).

Since the mid-1980s China shows the highest coal shares on total electricity output compared to the other three countries (see Figure 9). In 2010, more than 80 % of the Chinese electricity production was based on coal. Germany, on the other hand, shows an opposite development. The coal share decreased substantially since the 1960's from 87% in 1960 to 44% in 2010.

The USA shows a relatively stable share of coal-based power generation of around 50%. Japan has seen a very instable role of coal throughout the course of time. After a decrease before 1975 the share of coal rose again. Currently coal contributes 24.9% in 2010 to support Japan's power supply.

Figure 10: CO_2 intensity of total electricity and heat output in selected countries

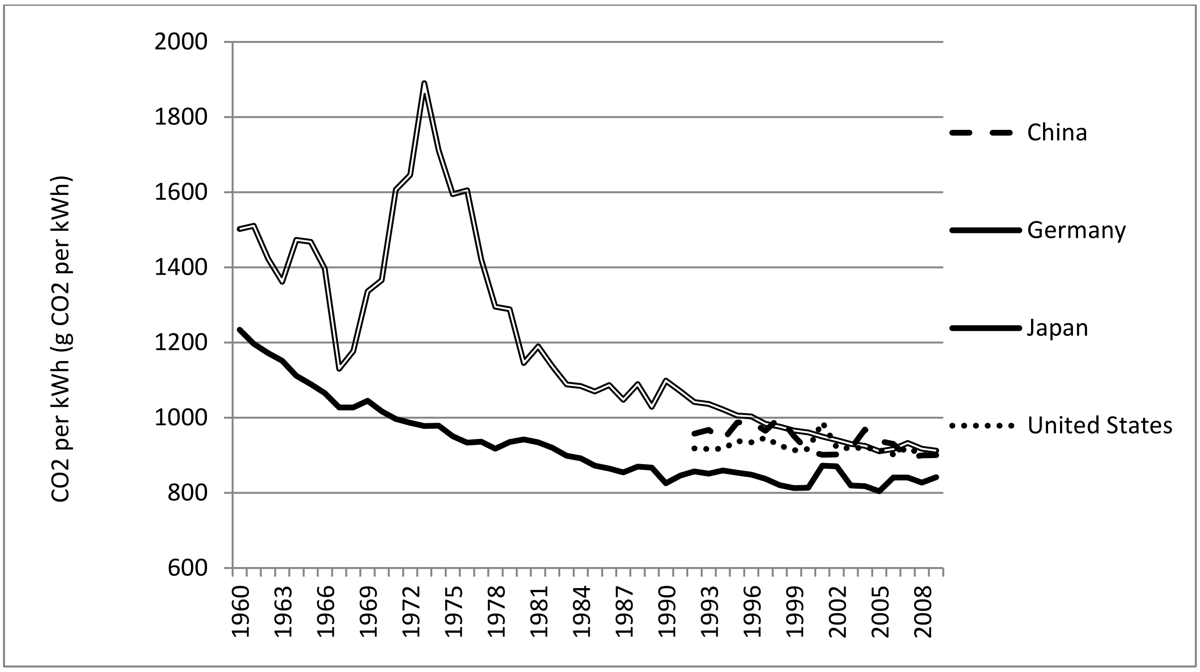


Source: IEA (2010b). *data was missing in China and Unite State before1992

CO_2 intensity of electricity production can also be regarded as indicator for demand advantages. As climate change became the global issue, countries with high CO_2 emission and high CO_2 intensity of electricity from coal face high political pressure from other countries to improve their CO_2 performance. These countries will likely invest in low carbon technologies, including clean coal. A limitation of this indicator is that countries with a high CO_2 intensity of the electricity sector may also switch to other energy resources such as renewables to produce electricity. Figure 10 and 11 show CO_2 intensity of total electricity and heat output and from coal source in the selected countries.

The two figures show that there is a declining trend regarding CO_2 intensity of electricity and heat output in the selected countries. Due to a still high CO_2 intensity of total electricity, China and USA have a relative demand advantage. However the advantages become smaller regarding the CO_2 intensity of electricity and heat output from coal.

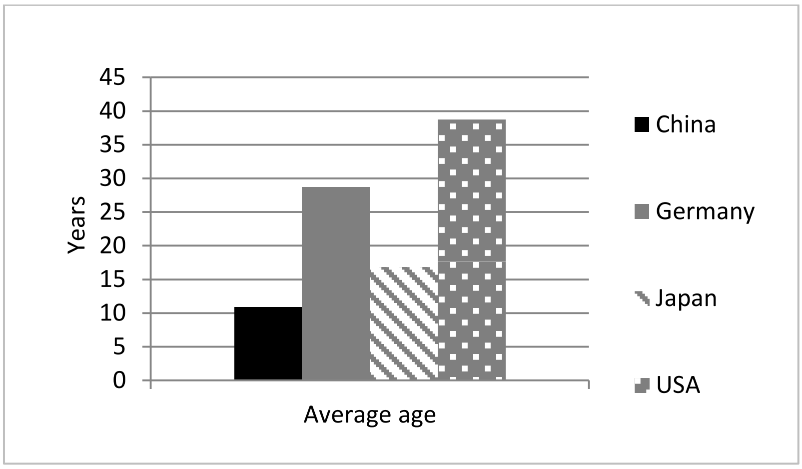
Figure 11: CO2 intensity of electricity and heat output from coal in selected countries



Source: IEA (2010b). * data was missing in China and USA before1992

The average age of power stations, as shown in Figure 12, can be seen as the last indicator for demand advantages. Countries characterized by high average plant age have a demand advantage since the power plants can be expected to be replaced soon. Coal-fired power plants do usually run for a period of 25-35 years. The United States has the highest average age of their coal-fired power plants.

Figure 12: Average age of coal-fired power plants in selected countries in 2010

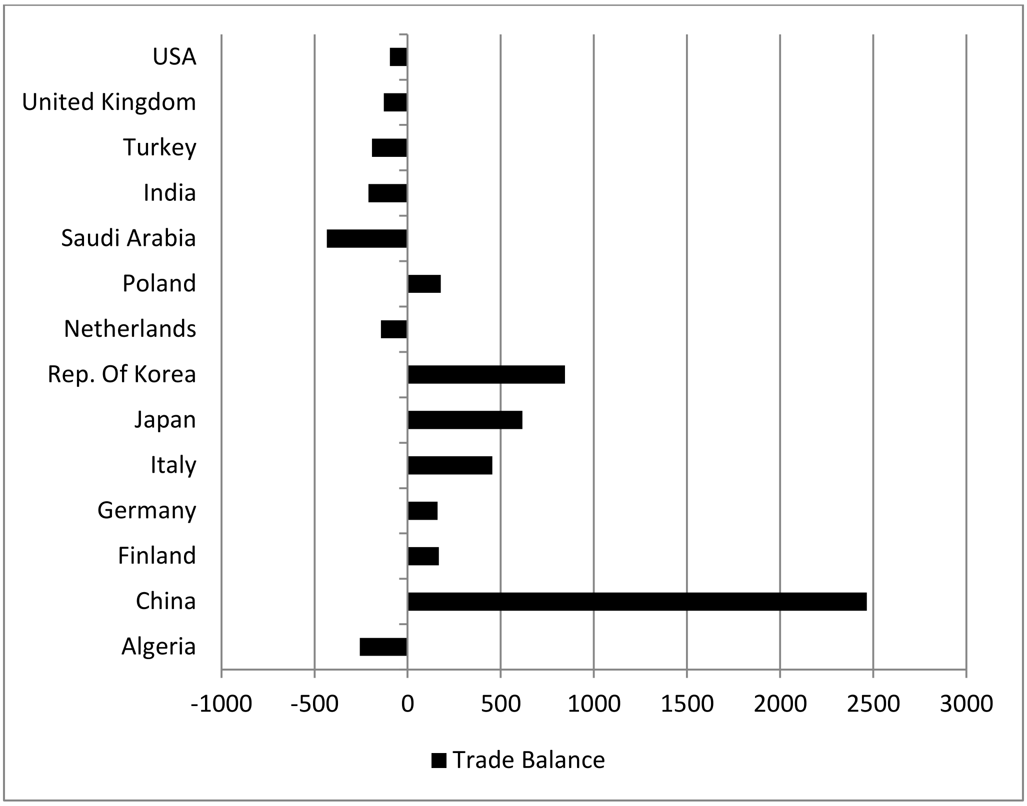


Source: IEA (2011a).

4.3 Export advantage

In the following, we try to assess which countries are specialized in the production of clean coal technologies and successful in selling clean coal equipment to other countries. To measure the export advantage, we use the trade balance (exports – import) in 2010 and the development of the export/import ratio from 2007 to 2010. The UN Comtrade data basis provides such data not explicitly for clean coal technologies but for the product groups “steam boilers” and “steam turbines”.

Figure 13: Trade Balance Steam Boilers in 2010, in millions US $



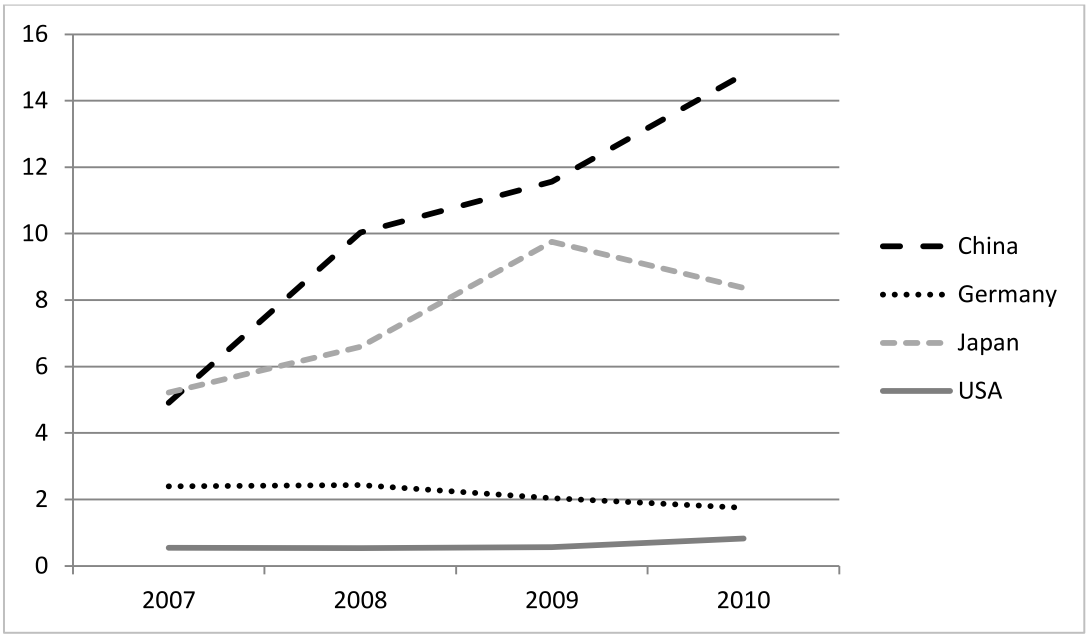
Source: UN (2012).

Figure 13 shows that China is highly specialized in the production of steam boilers even dominating the Republic of Korea and Japan. Following the results of expert interviews with power plant and component producers (see also Section 6) this statistic does not tell the whole story because China predominantly exports parts of boilers that have to be completed by the high-tech products of Japanese or German firms. Japan and Germany are also net exporters of steam boilers whereas the USA is even a net importer.

The development of the export/import ratio from 2007 to 2010 confirms these results: From 2008 China shows the highest export/import ratio followed by also high values of Japan. For

Germany, this value even declined slightly from 2007 to 2010 confirming the lower importance of Germany as a production location for these products. In the USA, we observe a slight increase but the ratio remains below the value one.

Figure 14: Steam Boilers: Development of export-import ratios from 2007 to 2010

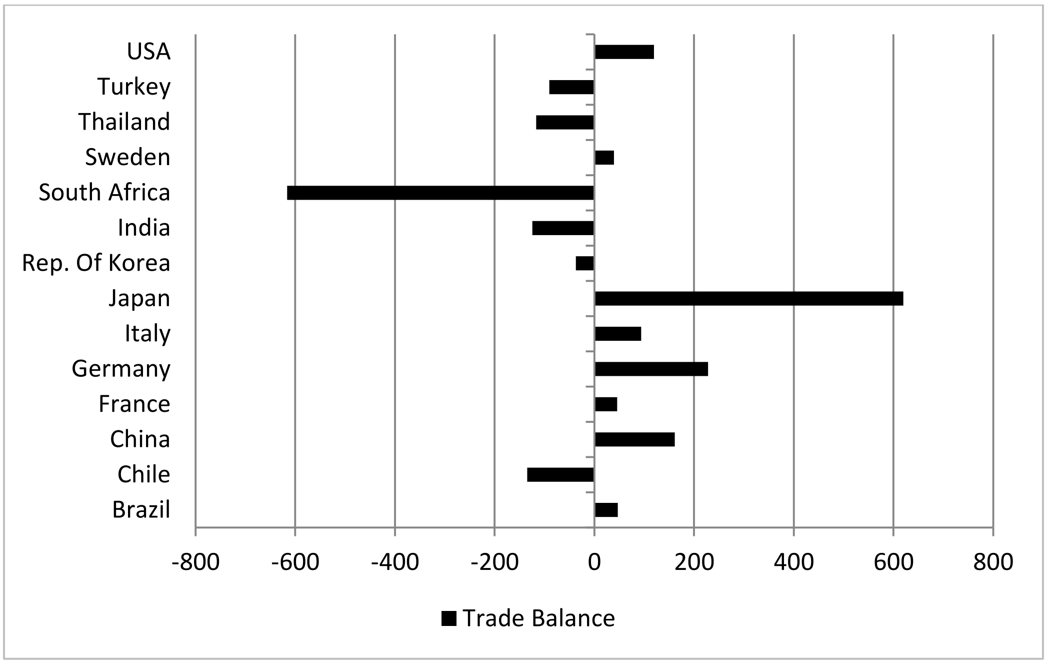


Source: UN (2012).

Concerning steam turbines, Japan seems to be the most specialized country documented by a high trade surplus in 2010 (Figure 15) and very high export/import ratios from 2007 to 2010 (Figure 16) compared to the other countries. Especially Germany, but also China and the USA also show high net exports in 2010 for steam turbines.

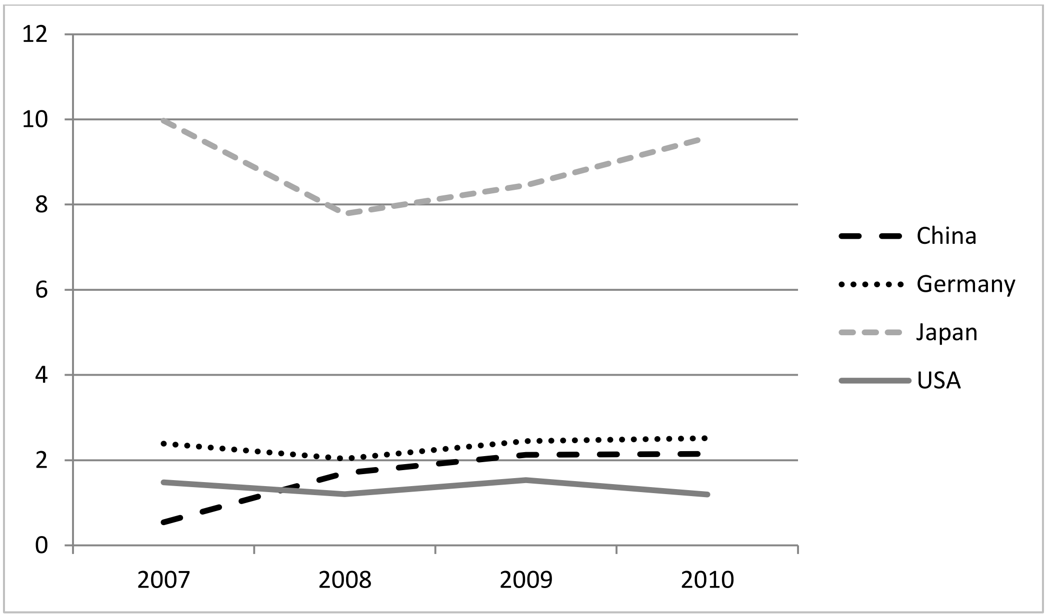
As concerns the trade balance and the export/import ratio, Germany still remains beyond China whereas the export/import ratio of the USA is now lower than that of China.

Figure 15: Trade Balance Steam Turbines in 2010, in millions US $



Source: UN (2012).

Figure 16: Steam Turbines: Development of export-import ratios from 2007 to 2010



Source: UN (2012).

Summing up, China seems to have an export advantage for steam boilers, whereas Japan holds this position for steam turbines. Due to the growing importance of highly efficient coal power plants requiring “high-tech” steam boilers, the Chinese producers will only keep their export advantage if they are able to improve the technical quality of their boilers.

4.4 Transfer advantage

On the one hand, the transfer advantage describes the capability of a country to be or to become a lead market in the respective technology. On the other hand, but closely correlated to the capability, a country shows a high transfer advantage if the international reputation and attention regarding the specific technology is high (see Rennings and Smidt 2010).
To measure the transfer advantage for efficient coal technologies, we use the following indicators:

- Degree to which R&D matters in a country;
- R&D related to coal technologies and CCS (Carbon Capture Storage);
- Number of demonstration plants in a country;
- Efficiency of coal fired power plants (Output of electricity sector/Input electricity sector).

Table 1: Indicators Transfer Advantage

Country	R&D in general (2007/8/9) in % of GDP	R&D related to coal and CCS (2010) in % of GDP	Number of demonstration plants (2007)	Average Efficiency of coal fired power plants (2005)
Germany	2.82	0.00086	8	39.0
Japan	3.44	0.00267	21	42.0
USA	2.79	0.00256	12	36.4
China	1.5	-	9	31.0

Source: OECD (2012), IEA (2011a), Rennings and Smidt (2010).

The results for our indicators (see Table 1) show a clear transfer advantage for Japan. The average efficiency of coal-fired power plants is the highest, furthermore Japan is characterized by the highest number of demonstration plants and percentage of R&D in general and also related to coal technologies.

Table 2: Total R&D related to Coal Technologies (including Carbon Capture Stor-age) and renewable resources in million US $ (2010 prices and exchange rates)

Countries and Technologies	2005	2008	2010
Germany			
Coal (production, preparation, transport)	10.462	41.359	12.008
CO_2 capture and storage	5.625	3.856	17.046
Renewable energy sources	127.823	160.589	248.403
Japan			
Coal (production, preparation, transport)	160.806	90.468	18.295
CO_2 capture and storage	-	42.153	127.372
Renewable energy sources	277.8	223.188	236.845
USA			
Coal (production, preparation, transport)	269.119	349.271	148.0
CO_2 capture and storage	69.5	196.264	225
Renewable energy sources	277.115	456.737	1310

Source: IEA (2012).

Compared to renewable energy sources, the total R&D expenses related to coal technologies are very small in Germany (see Table 2). In Japan, the research for renewables has also a high importance but the R&D expenses for clean coal technologies are still very high supporting the result that Japan has a transfer advantage. From 2005 to 2010, interestingly, the R&D expenses in Japan shifted significantly from coal production technologies to CCS what is also the case in the USA.

4.5 Regulation advantage

In the following, we analyze indicators describing the regulation environment for the realization of clean coal technologies in the US, Germany, Japan and China. “A country has a regulation advantage if the legal framework allows companies to plan on a mid- and long-term scale and at the same time exerts pressure on firms to come up with innovative ideas” (Rennings and Smidt 2010). To analyze a regulation advantage for clean coal technologies indicators such as the existence of carbon-taxes and/or an emissions trading system, the importance of renewable energy electricity production and the social acceptance of coal technologies are useful.

Because of the high relative CO_2-emissions of coal compared to other energy sources the introduction of carbon-taxes or the implementation of an emissions trading system seems to be a very important driver of clean coal technologies. Furthermore, a high proportion of renewable energy electricity production may exert a pressure on the coal sector to become more efficient and less CO_2 intensive. At least in the long run, energy policy decisions are dependent on the acceptance of the society – the story of nuclear power being an excellent example for this argument. On the one hand, a low social acceptance for coal may trigger activities to develop cleaner coal technologies. But on the other hand, due to the fact that it is difficult to explain to a non-technician that coal may be “clean”, the low social acceptance may also lead to a resistance against all “dirty” and “clean” coal technologies. Thus we will describe and compare the energy innovation systems and environmental policy in the four countries to identify which country has advantages regarding regulation.

Germany

Historical development

In the following, we give a short historical overview on the evolution of the coal policy in Germany showing drastic changes in the role of coal as energy source.[5]

The decade from **1970-1980** was still characterized by an explicit promotion of the production of electricity by hard coal. As a consequence of the so-called “3. Verstromungsgesetz” the electricity sector has been obliged to use a certain quantity of hard coal (justified by the security of electricity supply). On the other side, new oil or gas plants even needed an explicite permission. Furthermore, a subsidy compensating the high hauling cost for hard coal (“Steinkohlepfennig”) was introduced to reduce the burden for the energy suppliers (see Fuchs et al. 2011).

During this time period, the construction of sub-critical coal power plants with a degree of effectiveness of 35% dominated. But on the other side, a more strict environmental policy (especially the “Bundesimmissionsschutzgesetz”) emerged regulating the reduction of sulphur dioxide (SO_2) and NO_x (mainly by end-of-pipe measures).

During **1980-1990** more rigorous emission limits for SO_2, NO_x and dust have been introduced (“Großfeuerungsanlagenverordnung”). The second energy research program postulated an increase of energy efficiency and a reduction of energy imports. After the nuclear catastrophe in Tschernobyl (1986) the research in nuclear power technologies has been reduced. Because of the before-mentioned Großfeuerungsanlagenverordnung, six GW of old subcritical coal power plants were closed accompanied by an enlargement of electricity power-heat combina-

[5] For a comprehensive report see Fuchs et al. (2011).

tion (KWK), the construction of 11 GW new power plants on the basis of hard coal but despite the availability of supercritical technologies, most of the new power plants were still subcritical. The time period was also characterized by a further development of fluidized bed combustion (see Fuchs et al. 2011).

The coal policy from **1990-2000** was initially dominated by the reunification of Germany leading to high subsidization for new lignite based power plants in East Germany. The so-called "Kohlepfennig" was declared as illegal leading to a reduction of the use of hard coal in Germany, furthermore the restrictions for gas and oil fired power plants were abolished. As a consequence, only few hard coal based power plants with predominantly supercritical steam parameters (efficiency degrees of 43%) have been constructed. The liberalization of the energy market led to high cost pressures for the energy suppliers.

From **2000-2011** the energy policy in Germany was more and more oriented towards renewable energies. The 5^{th} and 6^{th} energy research program aims at making the energy system sustainable by using renewable energy. A well balanced energy mix using hard and brown coal shall be realized. An increase of energy efficiency against the background of increasing energy prices from 2005 to 2008 and a higher share of renewables connected with climate protection are in the focus. Concerning coal the use of CCS technologies has been proposed but the societal acceptance of this technology is very low in Germany.

The introduction of the CO_2 emission trade system can be understood as a disadvantage for the use of coal despite the fact that the prices of CO_2 emission permits remained moderate during this decade. Nevertheless, only few new fossil-based power plants have been constructed since 2000. The competition policy concerning energy was characterized by an introduction of a stock market for electricity and further liberalization of the electricity market.

In 2011, an agreement to phase-out nuclear energy was decided in Germany after the Fukushima accident, which may be a driver for the construction of new clean coal technologies.

Assessment of the regulation advantage for clean coal technologies in Germany

The general policy background for coal technologies in Germany is characterized by a low societal acceptance whereas the high subsidized renewable energies are in the focus of energy policy. As already shown, the coal policy strategy has strongly changed during 1970 to 2011 but the sixth energy research program of the German government from 2011 still contains important elements to promote clean coal technologies. An important institution is COORE-

TEC denoting CO_2 reduction technologies (see Bundesministerium für Wirtschaft und Technologie, 2011) for the use of fossil fuels. This initiative aims at

- an improvement of energy efficiency in fossil-fuel-fired power plants;
- the promotion of Carbon Capture Storage (CCS) technologies;
- system integration of power plants, network optimization, better connection of power plants with industrial processes.

Furthermore, European initiatives play an important role. Already in 1998, a group of major suppliers to the power industry and some of the major utilities in Europe started a 17-year demonstration project that was financially supported by the European Commission (European Commission 2011:74), namely the so-called Thermie 700°C. “The main aim of the THERMIE 700 °C steam coal power plant project is to make the jump from using steels to nickel-based super alloys for the highest temperatures in the steam cycle which should enable efficiencies in the range of 50-55 % to be achieved.” (European Commission 2011:74).

As regards the German innovation policy, the sixth energy research program shows that coal technologies are not in the focus of innovation policy and subsidies because of the high attention towards renewables but the program confirms that the improvement of the use of coal for electricity production is necessary despite a low societal acceptance. In fact, the environmental policy goes in a similar direction. Renewable energy is highly subsidized, on the other side eco-taxes and the European Emission Trade System (ETS) lead to a higher burden of fossil fuel energy suppliers and energy consumers. The negative effect of environmental policy (e. g. ETS) is moderated because the amount of permits for energy suppliers were high and mainly costless because a grandfathering allocation system was still in use. Furthermore, there are still exceptions for energy suppliers concerning eco-taxes. From the side of the industrial policy, too, the liberalization of the electricity market led to a higher competition and costs for fossil fuel energy suppliers.

In a nutshell, Germany lost much of its regulation advantage for clean coal technologies during the last ten years because of a clear cut change of paradigm towards renewables. It may be true that this new strategy also triggers the development of more efficient coal technologies but on the other hand the coal sector lost much of its financial support by the state in favor of renewables. In the long run, it can be expected that the low societal acceptance of coal will lead to a further loss of regulation advantage for clean coal technologies.

China

Historical development of “clean coal policy”

Subcritical coal power plants dominated in China until 2000. Whereas significant supercritical technologies are observable only from beginning of 2004, the installation of ultra-supercritical capacities began in 2007. Historically, the decade from **1970-1980** is characterized by inefficiencies of the innovation system (see Fuchs et al. 2011): A strict state control on innovation activities was accompanied by low R&D spending. In absence of environmental regulation measures exclusively subcritical technologies have been used. Furthermore, some plants with Circulated Fluidized Bed Combustion (CFBC) with low efficiency but allowing to burn cheap coal were constructed.

From **1980-1990** the Chinese economy grew by 15% per year, first considerable foreign direct investment was observed. This decade also showed first measures to protect the environment: 1984 Pollution Prevention and Control Law, 1987 Air Pollution Prevention and Control Law, 1989 Environmental Protection Law of the People's Republic of China (see Fuchs et al. 2011). The Chinese government tried to promote high technology innovation activities: National High Technology Research and Development Program und the Torch Program (high and emerging technology industry development program) but the lack of protection of knowledge in China led to low incentives for foreign investors to use new technologies, furthermore the overall spending in R&D was still low. Furthermore, state-regulated low electricity prices reduced the incentives to invest in clean coal technologies (see Fuchs et al. 2011).

During **1990-2000** the national innovation system was strengthened by the National Basic Research program: promotion of research in agriculture, energy, environmental issues, information and communication technologies. China introduced a law for the electricity sector to trigger investments and higher emission limits for power plants but they were still significantly lower compared to other countries. A further aim was the increase of energy efficiency: Law of the People's Republic of China on Conserving Energy.

Concerning coal technologies, China promoted FBC technologies and also IGCC. Joint ventures (e.g. Dongfang and Hitachi Company (Japan), Shanghai Electric and Siemens) and license contracts Harbin and Pyro-Power Company, Dongfang and Foster&Wheeler aimed at improving the technological performance of Chinese coal fired power plants. Furthermore, a closer cooperation between Japan and China for the construction of power plants has been realized. In 1992, first supercritical power plants were constructed.

During **2000-2011** the high energy demand in connection with higher energy prices increased the pressure to develop more efficient power plants. The 11th five-year-plan contained the goal of a reduction of energy consumption per unit of GDP by 20% to increase energy efficiency. Concerning technology, the medium and long term energy conservation plan intended to use more FDC technologies and heat-power combinations and an increase of R&D in IGCC technologies. During this decade, China became a member of WTO, foreign direct investment and foreign R&D in China has been enlarged significantly (see Fuchs et al. 2011).

Assessment of the regulation advantage for clean coal technologies in China

The general policy conditions for the use of coal power plants in China are – against the background of a still highly growing energy demand – favorable, despite a growing consciousness of politicians and population for environmental measures. Following Hong et al. (2009), China has tightened its environmental protection laws and standards during the recent years. Environmental protection in the power industry is mainly carried out through the State Electricity Regulation Commission. “At the end of 2001 China’s State Environmental Protection Administration initiated the national 10th Five-Year Plan for Environmental Protection to address the grim situation of environmental protection in China. The plan proposed energy-conservation and emission-reduction goals specifying that by 2005 sulphur dioxide emissions from the power industry would be reduced by 10 to 20 per cent from 2000 levels and the average coal consumption of coal-fired power plants would drop to 15 to 20 grams per kilowatt-hour below 2000 levels.” (Hong et al., 2009:20).

The 11th Five-Year Plan of the Chinese government aims at restructuring the energy sector by shutting down high polluting and energy-consuming small thermal power plants: “In 2007 the State Council proposed the closure of 50 gigawatts of thermal power units during the period of the 11th Five-Year Plan, replacing them with the installed capacity of larger and more energy-saving superscale or ultra-superscale thermal power units. This means that 12 gigawatts to 13 gigawatts will be closed down annually.” (Hong et al., 2009:22).

The industrial policy of the Chinese government aims at increasing the energy efficiency in energy-intensive sectors such as steel and electrolytic aluminum industries “ … in order to substantially lift entry barriers in terms of energy efficiency and to speed up the elimination of small steel-making and thermal power.” (Hong et al., 2009:22). In Article 31 of the law on Energy Conservation, “…the state encourages industrial enterprises to adopt highly efficient and energy-saving motors, boilers, furnaces, fans and pumps, and to employ co-generation technology, residual heating and pressure utilization, clean coal technology and advanced energy monitoring and control technologies." (Hong et al., 2009:20). In fact, from 2001 to 2011, 21 ultra-supercritical coal-fired power plants were constructed in China.

To sum up, in China, the regulation situation seems to be positive for the implementation of clean coal technologies. On the one hand, because of the high and still growing energy demand connected with enormous coal reserves, China will not renounce the use of coal. On the other hand, a growing environmental consciousness of politicians and parts of the population trigger the development of cleaner coal technologies. The construction of ultra-supercritical coal-fired power plants during the last years confirms this argumentation.

Japan

Historical development

In the early 1970s Japan had a quite one-sided alignment towards oil. After the oil crises in 1973 and 1979, a more balanced energy mix was developed. The "Law concerning Rational Use if Energy" was passed and R&D expenditure for coal increased obviously, for example coal liquefaction (see Fuchs et al. 2011).

The "Alternative Energy Law" was passed to promote alternative energy sources for oil and a prohibition for building oil power plants. Central elements of R&D was circulating fluidized bed combustion, pressurized fluidized bed combustion and the development of power plants with ultra-supercritical steam parameters to lower costs and raise efficiency (see Fuchs et al. 2011).

In 1995, the first "Science and Technology Basic Law" was adopted and specified by the "Science and Technology Basic Plan". Japan also began to liberalize its energy market. One year later a voluntary agreement to lower CO_2 emissions was enacted, inter alia "The Federation of Electric Power Companies of Japan" concluded to lower the CO_2 emissions per unit of output about 20%. Several possibilities to achieve this goal were mentioned: more nuclear power plants, a raise of efficiency of power plants and the use of new techniques (renewable energy). Research still focused on fluidized bed combustion and IGCC technology (see Fuchs et al. 2011).

In 2001 and 2006, new Science and Technology Basic Plans were established. The "Basic Energy Plan" and "Strategic Energy Plan" aim among other things for a reduction of dependence on imports and a raise of CO_2-free energy production to over 70%. For this purpose, an obvious reduction of CO_2 emissions of new coal power plants was planned. Furthermore, Japan proceeded with liberalizing their energy market and continued research in the IGCC technology sector (see Fuchs et al. 2011).

After the catastrophe of Fukushima in 2011 there was nearly no social acceptance for nuclear energy (Meltzer 2011). To close the gap left behind by nuclear power plants Japan is forced to raise the amount of coal and especially oil/gas power which will lead to increased costs of imports. Currently Japan is working out a new energy concept (see Hünteler et al., 2012).

Assessment of the regulation advantage for clean coal technologies in Japan

Especially the Japanese innovation policy seems to be favorable for the development of clean coal technologies because of the focus on highly efficient power plants. The R&D subsidies are high and co-operations between universities and the industry are actively supported. The relatively high amount of ultra-supercritical power plants constructed during the last twenty years confirms this picture. In fact, Japan is forced to develop and use highly efficient coal technologies because the country is highly dependent on imports of energy. On the other side, the Japanese energy firms are strongly export oriented so that they are forced to develop new and efficient technologies that may be sold on the world market.

In future, against the background of the high risk of nuclear power plants in Japan, efficient clean coal technologies may still play a more important role.

USA

Historical development

In the 70ies subcritical power plants dominated, but, interestingly, in 1959/1960 the USA constructed the first ultra-supercritical coal-fired power plant but abandoned this technology nearly completely. First measures to reduce the dependence from oil reserves took place, e.g. the Public Utility Regulatory Policies Act promoting renewable energy and opening electricity markets, and the Energy Tax Act reducing charges for solar, wind and geothermal heat. The use of oil and gas in the industrial sector was limited by an enlargement of R&D for the energy sector, by promoting of PFBC allowing for higher efficiency and the by use of low-quality coal (see Fuchs et al. 2011).

In the 80ies, under the Reagan-Government, deregulation and a reduction of public R&D started. A Clean Coal Technology Program was introduced due to the discussion of acid rain.

The policy continued in the 90ies with the Energy Policy Act of 1992. This led to a further opening of the electricity market leading to an increase of the construction of gas-fired power plants due to their low investment costs and due to generally low gas prices and high reserves of gas in the USA (see Fuchs et al. 2011).

During the past decade oil prices increased drastically, and a Climate Change Technology Program (CCPT) was introduced: The goal is to reduce greenhouse gas emissions and to further develop clean coal technologies such as IGCC and CCS, new nuclear power plants and more renewable energy. The Clean Coal Power Initiative (CCPI) developed and commercialized new coal technologies, especially CCS and IGCC (see Fuchs et al. 2011).

Today, the USA experiences a new natural gas boom. One reason consists in the new environmental targets of less CO_2 emissions. The combustion of natural gas emits less CO_2 and SO_2. Combined cycle power plants only emit the half compared to an equivalent coal power plant. The second reason is the increasing gas supply in the USA accompanied by decreasing prizes. Due to the hydraulic fracturing technology, unconventional new resources that were not profitable up to now, can be extracted (Energy in Brief, 2012). So it has been estimated that 500 coal power plants can be replaced by new natural gas power plants (Handelsblatt, 2011).

Assessment of the regulation advantage for clean coal technologies in USA

The development of efficient energy technologies is mainly market-driven, there is only few public R&D support. Concerning coal technologies, the USA show a concentration on IGCC and Fluidized Bed Combustion. Despite the fact that the first ultra-supercritical power plant was constructed in the USA in 1959, this country abandoned this technology. Furthermore, the environmental policy regarding a CO_2 emission reduction strategy is quite lax. In fact, there seems to be no regulation advantage for the USA concerning clean coal technologies.

To sum up, compared to the US, Germany and Japan, China seems to have a regulation advantage concerning clean coal technologies.

5 Market structure, lead suppliers and technological capability

The recent literature on lead markets (e.g. Rennings and Cleff 2011 or Tiwari and Herstatt 2011) accentuates the role and the importance of supply side aspects for the developments of lead markets. A competitive market structure combined with the existence of highly innovative lead suppliers may be the basis of the leadership of a country in a specific technology. Therefore, we firstly analyse the market structure for coal technologies combined with an identification of the respective lead suppliers. Secondly, we analyse the framework conditions for competition and innovation in our four countries followed by a deeper analysis of the technology capabilities using patent indicators.

The question which market structure is best for the realization of innovations has a long tradition in the theoretical literature on innovation behaviour of firms. Following Arrow (1962), firms in competitive markets have higher incentives to invest in R&D because they may get – at least for a limited period of time - the full economic rent from an innovation. Contrary to that, Schumpeter (1943) argues that big firms in monopolistic markets are more likely to solve the appropriation problem, namely to keep the rents of their innovation. Therefore, the role of the market structure remains an empirical question. Many empirical analyses support the view of Arrow, but especially the more capital intensive the industry and the respective innovation activities, large firms in monopolistic markets may also be more innovative (see Martin 2006).

Concerning coal technologies, the markets in our four countries seem to be highly concentrated. Table 3 shows the shares of the “big five” producers of whole components, turbine and boiler suppliers. Following this indicator, the markets in Japan and the USA are characterized by the highest concentration whereas the situation in Germany seems to be a bit more competitive.

Table 3: Number of clean coal technology suppliers

Country	Producers of coal power plants		Turbine suppliers		Boiler Suppliers	
	Number	Share* of "big five" in %	Number	Share* of "big five" in %	Number	Share* of "big five" in %
China	23	81	27	83	22	80
Germany	17	71	18	87	19	63
Japan	6	99	7	99	6	99
USA	20	96	12	95	20	96

* Related to the number of plants.
Please note that the IEA Coal database contains many missing values concerning the names of the producers. The "shares of the big five" are calculated without missing values implicitly assuming that the plants without producer information show the same distribution.

Source: IEA (2011a).

The Lead Suppliers (number of constructed plants in brackets) in the different countries are as follows:

China:

Shanghai Boiler Works Company (330), Harbin Power Engineering (294), *Shanghai Electric Corporation (243)*, Dongfang Electric Corporation (222), Wuhan Boiler Works (103)

Germany:

Hitachi Power Europe (44), *Shanghai Electric Corporation (39)*, L. und C. Steinmüller GmbH (22), EVT Energie und Verfahrenstechnik GmbH (16), Dampferzeugerbau Berlin (15)

Japan:

Mitsubishi Heavy Industries (29), Babcock Hitachi KK (19), Ishikawajima-Harima Heavy Industries (17), *Shanghai Electric Corporation (12)*, Kawasaki Heavy Industries (5)

USA:

ABB Combustion Engineering (393), Babcock and Wilcox (358), Foster Wheeler (122), *Shanghai Electric Corporation (118)*, Riley Stoker Corporation (93)

Interestingly, the Chinese company “*Shanghai Electric Corporation”* constructs power plants in all of the considered countries showing the rising importance of China for coal technologies.

On the background of the above mentioned controversial theoretical debate and the fact that the development and the construction of new clean coal based power plants is capital intensive the identification of a market structure advantage of any of the four countries is - following our concentration indicator - not possible.

Therefore, it is furthermore useful to explore the general competition conditions in the four countries on the basis on the Global Competitiveness Report of 2011. This report contains a rich set of indicators on innovation and the respective framework conditions (see Table 4).

The overall Global Competitiveness Index (GCI) shows the highest rank for the USA (5) followed by Germany (6) and Japan (9). China already reaches rank 26. To assess the conditions for the development of new (clean coal) technologies it is more interesting to look at subgroups of the GCI especially on innovation indicators and those that describe the efficiency of the goods market.

The innovation indicators show a dominant role of Japan: First ranks on the capacity of innovation, company spending on R&D and a second rank for the availability of scientists and engineers seeming to be a problem for Germany only reaching the last rank of the four countries (41). Concerning the patents granted (2), the state of the cluster development (3) and for the firm-level technology absorption (3) Japan also attains the highest values of the four countries. Besides variables on trade barriers and rules on FDI, Japan shows high values for the variables on good market efficiency, too. The intensity of local competition (rank 4) and the effectiveness of anti-monopoly policy (rank 9) also seem to be very high in Japan.

The USA also reaches high ranks but mostly behind Japan except e.g. the quality of scientific research institutions (rank 7), the government procurement of advanced technical products (9, the availability of latest technologies (13) and the venture capital availability (12).

Germany also shows high innovation capacities (3) and a high quality of scientific research institutions (10). Comparing the four countries, Germany reaches the best positions regarding the quality of the educational system (17), the quality of the overall infrastructure (10) and the intellectual property protection (13). Concerning this indicator, China only attains a low rank (47). That is also the case for the effectiveness of anti-monopoly policy (48) and especially for the existence of bureaucratic barriers in this country measured by the number of procedures to start a business (131). Compared to the other three countries, the innovation capacities in China still seem to be quite low.

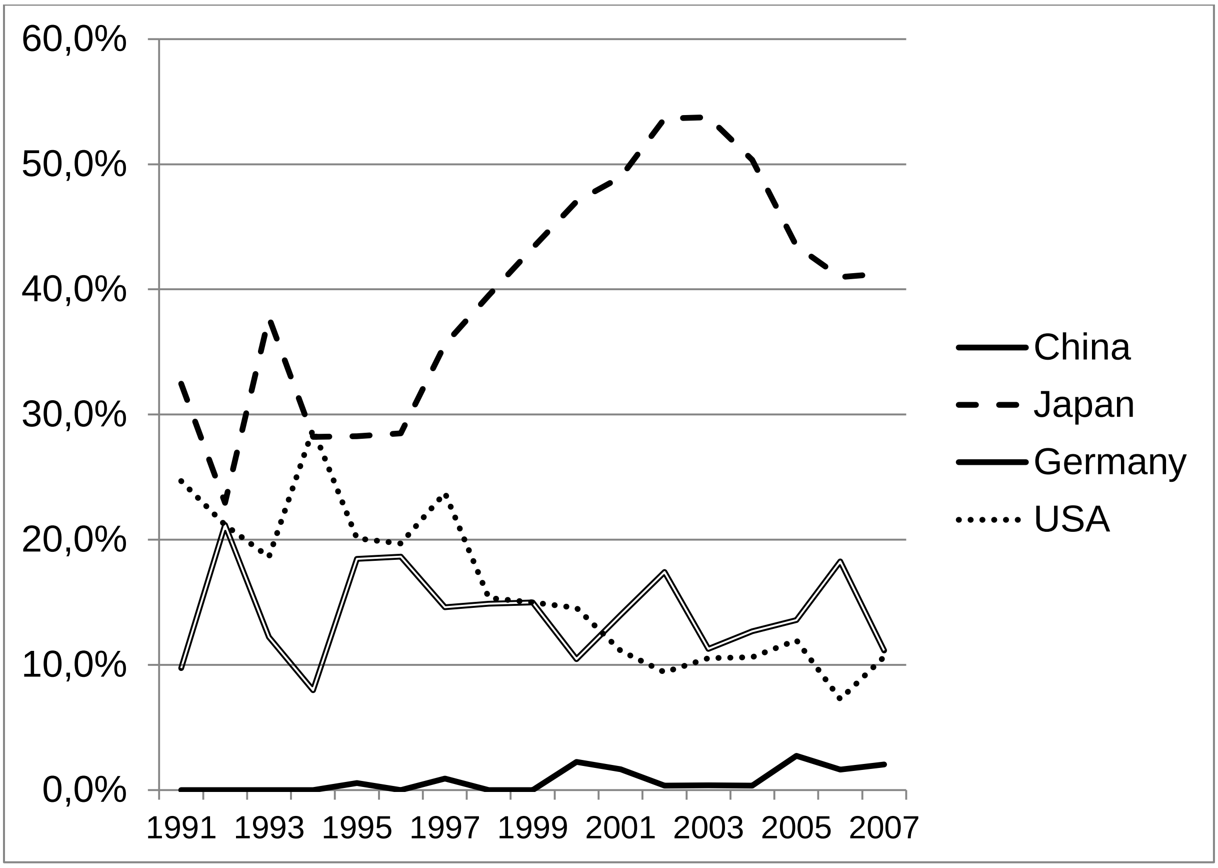
Table 4: Indicators from the Global Competitiveness Report

Indicator	China		Germany		Japan		USA	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank
GCI 2011-2012	4.9	26	5.4	6	5.4	9	5.4	5
Good market efficiency								
Intensity of local competition	5.5	22	5.8	9	5.9	4	5.6	18
Extent of market dominance	4.7	20	5.7	3	5.8	2	5.2	11
Effectiveness of anti-monopoly policy	4.3	48	4.9	23	5.2	9	5.0	17
No. of procedures to start a business	14	131	9	94	8	78	6	34
Prevalence of trade barriers	4.5	63	4.7	49	4.1	100	4.6	59
Business impact of rules on FDI	5.3	22	4.6	72	4.5	87	4.7	68
Innovation indicators								
Capacity for innovation	4.2	23	5.7	3	5.8	1	5.2	7
Quality of scientific research institutions	4.3	38	5.6	10	5.5	11	5.8	7
Company spending on R&D	4.2	23	5.5	5	5.9	1	5.3	6
University-industry collaboration in R&D	4.5	29	5.2	13	5.1	16	5.7	3
Gov´t procurement of advanced technical products	4.4	16	4.2	29	4.1	32	4.7	9
Availability of scientists and engi-	4.6	33	4.5	41	5.8	2	5.5	4
neers	2.0	46	150.6	9	352.9	2	339.4	3
Utility patents granted/mill. popu-	4.7	17	4.9	13	5.3	3	5.1	9
lation	4.5	100	6.2	20	6.3	15	6.0	13
State of cluster development	4.9	61	5.9	14	6.3	3	5.9	18
Availability of latest technologies	4.6	80	4.3	92	4.7	65	4.9	49
Firm-level technology absorption	3.5	22	3.0	37	2.9	47	4.0	12
FDI and technology transfer								
Venture capital availability								
Further indicators	4.0	54	4.9	17	4.4	36	4.7	26
	4.2	69	6.2	10	6.0	13	5.7	24
Quality of the educational system	5.5	49	6.7	11	6.5	17	6.0	32
Quality of overall infrastructure	4.0	47	5.6	13	5.3	22	5.0	28
Quality of electricity supply	3.9	21	3.0	88	3.2	73	3.4	58
Intellectual property protection	4.7	41	5.0	28	4.8	38	4.5	50
Burden of government regulation	5.0	77	5.0	77	7.0	16	8.3	5
Transparency of government policy								
Strength of investor protection								

Source: World Economic Forum (2011).

The technological capabilities of the different countries with respect to coal technologies can be measured by the importance of the respective patent activities. Figure 17 shows the world market shares of coal fired power plant technologies in the four countries documenting the high technology capabilities of Japan with a share of 40% in 2007. In the USA, the market share declined from 1991 to 2007 showing the diminishing interest and capability of this country in the development of clean coal technologies. In Germany, the patent shares are stagnating whereas the figures for China are rising but starting at a very low level.

Figure 17: World Market Share Patents: Coal-fired Power Plant Technologies



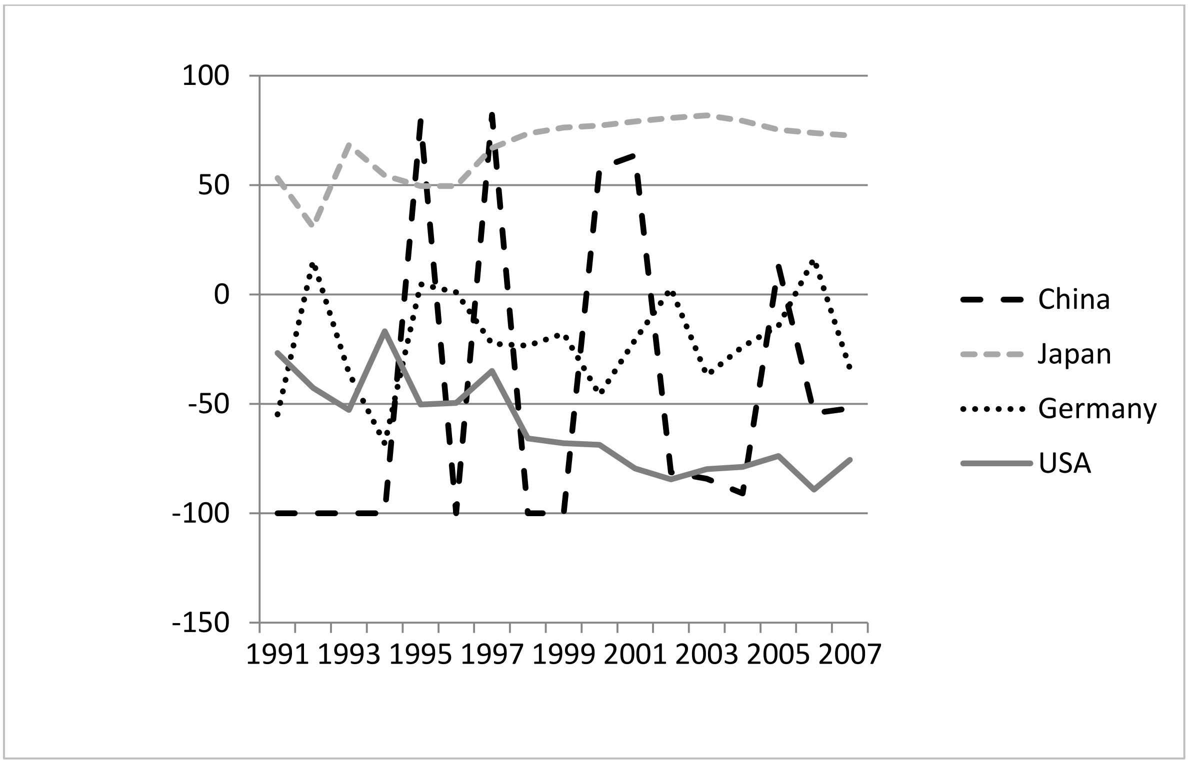
Source: ISI (2012).

Furthermore, the Relative Patent Advantage is calculated for each country *i* and each technology field *j* according to (see Walz and Marscheider-Weidemann (2011)):

$$RPA_{ij} = 100 * \tanh \ln\{(p_{ij}/\sum_i p_{ij})/(\sum_j p_{ij}/\sum_{ij} p_{ij})\}$$

The RPA indicates if the world patent share of clean coal technologies of a country is bigger or smaller than the country´s world patent share for all technologies.
The RPA values confirm the picture obtained for the world patent shares (see Figure 18).

Figure 18: Relative Patent Advantage for Coal-fired Power Plant Technologies



Source: ISI (2012).

For all years from 1991 to 2007, only Japan shows positive figures documenting its leading technological capabilities for clean coal technologies. The RPA values also confirm the decline of the importance of coal technologies for the USA. Because of low absolute values for the number of coal related patents the figures for China do not yet show a clear picture. The stagnating situation for Germany regarding clean coal technology capabilities is confirmed.

To sum up, all countries are characterized by high concentration values for coal technology suppliers so that further indicators have to be analysed to assess a market structure advantage. Once again, Japan seems to be on top of the four countries because of its high innovation capacities and the high availability of scientists and engineers.

6 Firm views and strategies – results from expert interviews

To analyze the strategies of firms regarding the development and use of new efficient coal technologies against the background of a growing political support of renewables expert interviews were carried out. A producer of components for coal based power plants (Saarschmiede), a power plant producer (Hitachi Power Europe) and an energy supplier (Vattenfall) were interviewed.

The expert interviews aimed at analyzing

- the existence and the role of first mover advantages concerning efficient coal technologies including the countries China, Germany, Japan and the USA;
- how component suppliers, power plant producers and energy suppliers react to energy policy changes especially in Germany.

Presentation of the questioned firms

Saarschmiede produces components for (coal fired) power plants (e. g. turbine & generator shafts, turbine & compressor rings, parts for plant construction or high pressure vessels). Germany remains the main market (37%) followed by Europe (23%), Asia (23%) and the USA (15%). Whereas the construction of completely new power plants plays an important role in China and India, in Germany and especially in the USA, the refurbishment of existing power plants dominate. The Saarschmiede may be characterized as one of the world market leaders regarding high quality steel components for power plants, the main competitors are coming from Japan (Japan Steel Works, Japan Casting and Forging Corporation) or from Europe (Böhler, Germany or Terni Steel, Italy) whereas competitors from the USA do not play an important role. The main customers in Europe are Siemens, Alstom or GE but the Chinese market gains importance (Shanghai Boiler Works, Harbin Power Engineering or Dongfang Electric Corporation as clients of Saarschmiede).

Hitachi Power Europe is one of the main constructors of fossil fired power plants (especially coal fired and nuclear based power plants). Whereas the rapidly growing market of China is supplied by other firms of the Hitachi group, Hitachi Power Europe concentrates on the construction of new power plants in Europe (especially Poland, Turkey and Russia), India and

South-Africa. In Germany, the company increasingly concentrates on services and refurbishment for existing power plants because, at the moment, nearly no new coal fired power plant projects are planned. The main competitors concerning boilers are Alstom and IHI and Siemens with regard to turbines.

Vattenfall is an energy supplier mainly producing electricity by lignite (80%). Concerning electricity production, Vattenfall has a market share of 16% in Germany. The main competitors are RWE, EON and EnBW. The main constructors of the power plants of Vattenfall are Hitachi Power Europe, Alstom and Siemens.

Market development in Germany, China, Japan and the USA

At present, the market for (clean) coal technologies in Germany is negatively assessed because of the high political support of renewables in combination with uncertainties concerning the future role of coal technologies. Nevertheless, the experts of Hitachi and Vattenfall are optimistic that coal technologies will play even a growing role to assure the energy supply in Germany, especially by the use of lignite based highly efficient power plants. At the moment, only refurbishment of existing coal power plants and services are important business areas whereas nearly no new projects are realized. In Japan, the future role of nuclear power is uncertain, but the experts do not expect a dynamic development concerning coal fired power plants. The market in China is very dynamic, around 50 new power plants are built every year leading to extensive possibilities to implement highly efficient technologies (ultra-supercritical). In the USA, at present, only few new coal fired power plants are constructed because of the high availability of gas but the high age of coal fired power plants (see Section 4.2) leads to high refurbishment potentials and markets.

Future dominating efficient coal technologies

Super and ultra-supercritical technologies will dominate other coal based technologies such as fluidized bed combustion, the future of advanced ultra-supercritical (700°C power plants) is unclear because of high investment costs and technology risks. Especially in Germany, lignite drying will be useful to increase efficiency of lignite based power plants. In the distant future Carbon Capture Storage (CCS) may play an important role but this development is strongly dependent on CO_2 prices and societal acceptance.

Assessment of the role of China as supplier

Following our analysis in Section 4.3, Japan and Germany still dominate the markets and the international trade for turbines, but concerning boilers China shows the highest export volume. According to our expert interviews, this picture is not totally true: China is specialized in low and middle temperature boilers, whereas the Chinese producers have still problems to produce high quality boilers. Even components supplied to German power plant producers have to be repaired and improved before they may be used. One expert assesses that China will be able to reduce their quality gap concerning boilers – an argument that may be confirmed by the Benson Boiler reference list of Siemens showing that Chinese firms (e. g. Dongfang Boiler Works) are able to produce boilers that are resistant to steam temperatures of more than 600 °C. Interestingly, following the new five-year-plan, China has decided to build a 700°C power plant. If this strategy will be successful, China would probably get the technological leadership. In fact, this seems to be highly uncertain because the Chinese innovation system is predominantly characterized by imitations and less by totally new technologies and products.

Concerning lignite based power plants, China is still not competitive, Hitachi and Alstom are market leaders.

Competition situation of coal technologies in Germany

Disregarding the negative external effects caused by the emissions of coal-based electricity production coal would be the cheapest solution among all energy carriers because of its reasonable cost of production and the high security of supply. The energy policy in Germany tries to internalize these negative external effects by taxes and emission permits (see also Section 4.5). Furthermore, renewable energies are highly subsidized. Nevertheless, the representatives of Hitachi and Vattenfall are optimistic that coal and especially lignite will play an important role in Germany at least up to 2050. Saarschmiede points to a growing importance to gas based electricity production.

Relevance of first mover advantages

Japan and Germany seem to have clear first mover advantages concerning the highly innovative parts of clean coal technologies and in general for 600 °C power plants whereas China has second mover advantages in manufacturing boilers. Following the experts, Germany has highly profited from these first mover advantages in terms of export success and technological leadership. The crucial question remains if the German firms are able to keep the first mover benefits against the background of the shrinking importance of coal technologies in Germany? Saarschmiede as a component producer is at least optimistic that the R&D units ("innovative cells") will not leave Germany or Japan despite of declining markets in these countries because of the lack of highly educated and innovative staff in China.

The experts of Hitachi and Vattenfall are more pessimistic. Germany and also Japan may lose their first mover advantages because a considerable part of innovation activities occurs when a power plant is constructed in close cooperation with the client. Due to the fact that nearly no new coal-fired power plants are projected in Germany, this country may lose a part of these first mover advantages. On the other side, the high market volume in China (nearly 50 power plants per year) leads to more innovation activities in this country. It is unclear if Chinese firms will be able to build a 700 °C power plant as intended in the five-year-plan but they will gain experiences and may get a technological leadership.

Following the opinion of Vattenfall, Germany will not lose its first mover advantages regarding lignite-based power plants.

An important pre-condition for keeping the technological leadership for efficient coal technologies would be the reduction of the high uncertainty regarding the future use of coal, whereas - on the other side - the profits for renewables are guaranteed. Following one expert, there is also a lack of qualified staff (engineers), an enlargement of cooperation with universities would be useful.

Strategic reactions of firms against the background of energy policy and the low societal acceptance of coal in Germany

Following the opinion of the questioned experts, the market situation in Germany for clean coal technologies requires far-reaching changes of firm strategies. For Saarschmiede, an increasing concentration on foreign markets is necessary because of the uncertainty regarding coal power plants in Germany, the firm will more and more concentrate on the Chinese market. At present, Hitachi Power Europe extends its business fields services, the refurbishment of existing power plants or the de-construction of nuclear power plants because, in Germany, the construction of new coal power plants will only be relevant in 5-10 years. Furthermore, the firm extends its activities in new markets such as Poland, Turkey or Romania whereas the Chinese market is not possible for Hitachi Power Europe. Despite these activities, Hitachi was forced to cut jobs.

On the one hand, Vattenfall will extend the use of renewable energies, on the other hand, the firm will still rely on lignite because under the condition of current and expected CO_2 prices this energy carrier will be competitive. A further option is the extension of R&D for CCS.

7 Summary and conclusions

Despite the high CO_2 emission intensity of fossil and especially coal fired energy production, these energy carriers will play an important role during the coming decades. The case study identifies the main technological trajectories concerning more efficient fossil fuel combustion and explores the potentials for lead markets for these technologies in China, Germany, Japan and the USA taking into account the different regulation schemes in these countries. We concentrate on technologies that have already left the demonstration phase. This is the case for supercritical (SC) and ultra-supercritical (USC) pulverized coal technologies that are already established.

An analysis of the diffusion of efficient coal technologies shows that the USA took over the role of a lead market in the 1960's and during the following 20 years. Other countries followed the American innovation design, such as Germany in the 1960's and Japan in the 1970's. The diffusion curves overlap by Japan in the early 1980's since America stopped to build new (ultra-) supercritical power plants. Although China is still the last country that introduced ultra-supercritical technologies in 2007, commercial adoption of this technology is expanding rapidly. The analysis shows that the typical pattern of a stable lead market only applies to a limited extent because Japan has surpassed the USA although it started as a typical lag market.

In a second step, we analyze the different lead market factors. The *price advantage* is described by hard and brown coal reserves, fuel prices and electricity generating costs. The USA and China show a clear price advantage regarding the coal reserves. Furthermore, China has the lowest generating costs so that, all in all, China seems to have the best position regarding the price advantage whereas Japan holds the last position because of the lack of reserves and high prices. High income per capita in the USA, Japan and Germany point to a *demand advantage* of these countries but high electricity intensity and the highest share of coal in electricity production (80%) favors China. The USA shows the highest average age of coal plants pointing to refurbishment potentials. To describe the *export advantage* the indicators “export minus import” and the “development of export/import ratio” has been used. China seems to have an export advantage for steam boilers, whereas Japan holds this position for steam turbines. Due to the growing importance of highly efficient coal power plants requiring “high-tech” steam boilers, the Chinese producers will only keep their export advantage if they are able to improve the technical quality of their boilers.

On the one hand, the *transfer advantage* describes the capability of a country to be or to become a lead market in the respective technology. On the other hand, but closely correlated to the capability, a country shows a high transfer advantage if the international reputation and attention regarding the specific technology is high. To measure the transfer advantage for efficient coal technologies, we use the indicators “degree to which R&D matters in a country”, “R&D related to coal technologies and CCS (Carbon Capture Storage)”, “number of demonstration plants in a country” and the “efficiency of coal fired power plants”. The results for our indicators show a clear transfer advantage for Japan. The average efficiency of coal-fired power plants is the highest, furthermore Japan is characterized by the highest number of demonstration plants and percentage of R&D in general and also related to coal technologies.

Germany lost much of its *regulation advantage* for clean coal technologies during the last ten years because of a clear cut change of paradigm towards renewables. It may be true that this new strategy also triggers the development of more efficient coal technologies but on the other hand the coal sector lost much of its financial support by the state in favor of renewables. In the long run, it can be expected that the low societal acceptance of coal will lead to a further loss of regulation advantage for clean coal technologies. On the other hand, in China, the regulation situation seems to be positive for the implementation of clean coal technologies. Chinese politicians will not renounce the use of coal because of the high and still growing energy demand connected with enormous coal reserves. Furthermore, a growing environmental consciousness of politicians and parts of the population triggers the development of cleaner coal technologies. Compared to the US, Germany and Japan, China seems to have a regulation advantage concerning clean coal technologies.

The analysis of *supply side factors* shows that all countries are characterized by high concentration values for coal technology suppliers. To assess a market structure advantage, further indicators have to be analysed. Japan seems to be on top of the four countries because of its high innovation capacities and the high availability of scientists and engineers and because of its leadership regarding clean coal patent activities.

All in all, Japan has caught up in terms of supply factors, China in terms of price, demand and regulation advantage. The fact that Japan is now the leading country for ultra-supercritical coal technologies supports the hypothesis that - apart from the demand-oriented lead market model - push factors such as R&D activity play a strong role as well. The advantage of Japan mainly stems from its intensive R&D activities. It can also be observed that some other advantages - such as price and demand advantage - are shifting to China. China is practicing a leapfrogging strategy, and has already become a leader in the market segment of low and middle quality boilers, whereas Japan and Germany still dominate the world turbine market.

To learn more about the reactions of firms towards a changing energy policy favoring renewables expert interviews were carried out. These interviews confirm that Japan and Germany seem to have clear first mover advantages concerning the highly innovative parts of clean coal technologies and in general for 600 °C power plants whereas China has second mover advantages in manufacturing boilers. The crucial question remains if the German firms are able to keep the first mover benefits against the background of the shrinking importance of coal technologies in Germany? Saarschmiede as a component producer is at least optimistic that the R&D units ("innovative cells") will not leave Germany or Japan despite of declining markets in these countries because of the lack of highly educated and innovative staff in China.

The experts of Hitachi and Vattenfall are more pessimistic. Germany and also Japan may lose their first mover advantages because a considerable part of innovation activities occurs when a power plant is constructed in close cooperation with the client. Due to the fact that nearly no new coal-fired power plants are projected in Germany, this country may lose a part of these first mover advantages.

Following the opinion of the questioned experts, the market situation in Germany for clean coal technologies requires far-reaching changes of firm strategies. For Saarschmiede, an increasing concentration on foreign markets is necessary because of the uncertainty regarding coal power plants in Germany, the firm will more and more concentrate on the Chinese market. At present, Hitachi Power Europe extends its business fields services, the refurbishment of existing power plants or the de-construction of nuclear power plants because, in Germany, the construction of new coal power plants will only be relevant in 5-10 years. Furthermore, the firm extends its activities in new markets such as Poland, Turkey or Romania. On the one hand, Vattenfall will extend the use of renewable energies, on the other hand, the firm will still rely on lignite because under the condition of current and expected CO_2 prices this energy carrier will be competitive.

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